THE PENETRATING BEAM

Reflections on Light

by Edith M. Levin

The Student Scientist Series, Edited by HARRY MILGROM

THE PENETRATING BEAM, REFLECTIONS ON LIGHT

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By
Edith M. Levin

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About the Author

Mrs. Edith M. Levin is the Assistant Principal for the Supervision of Science at Eastern District High School in Brooklyn, New York. Although her major subject area is Biology, she also supervises General Science, Chemistry, Physics, and Laboratory Techniques.

A graduate of Hunter College, Mrs. Levin holds a B.A. and has amassed seventy-seven credits above the baccalaureate in science and education courses taken as the need to acquire newer knowledge became apparent. She was a teacher for twenty-three years, serving one year in a junior high school and twenty-two at the senior high school level. She has been a science supervisor for eleven years.

Her professional affiliations include service as past vice-president of the New York Biology Teachers Association and past secretary-treasurer of the Biology Chairmens Association and membership in the New York Biology Teachers Association, the Biology Chairmens Association, the Physical Science Chairmens Association, the National Science Teachers Association, the National Association of Biology Teachers, and Phi Sigma.

Aside from science and science teaching, her interests include art, music, drama, reading, the psychology of learning, and now science writing.

Mrs. Levin believes that the following human factors are in large measure responsible for developing the knowledge we presently have and that which we will obtain in the future: curiosity—the ability to ask the right question; tenacity—the possession of will and skill to

search for the correct answer; and ability to recognize one or more correct answers when they present themselves.

It is the students' task to sharpen their basic skills in reading, math, writing, and speaking so that they will be able to satisfy their natural curiosity and communicate their findings to others. It is the educator's happy mission to inspire students to want to explore and learn; and then to help these students attain proficiency not only in the basic skills but also in those higher skills that will enable them to perceive the interrelationships among areas of knowledge that make all learning interdisciplinary.

To these ends, this book is dedicated.

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THE PENETRATING BEAM, REFLECTIONS ON LIGHT

I

The Nature and Sources of Light

The word "light" calls to mind so many thoughts: dawn, daybreak, brightness, clarity, understanding, cheerfulness, warmth, life.

All these, in fact life on earth itself, would be impossible without our sun. As you know, our sun is a star at the center of our solar system, with a diameter more than 100 times the diameter of the earth. It is a ball of gases so hot that they glow continuously. We say that these gases are incandescent. The sun possesses energy that comes to us through 93,000,000 miles of space as radiant energy. Some of this energy keeps us warm; some can bring us radio and television programs; some can operate batteries and engines; some helps grow our food through photosynthesis in green plants. A small portion goes through our bodies without our ever knowing it. A special part of the sun's radiation can send messages to our eyes for interpretation by our brain. This part of radiation we call visible light.

Sources of Light—Luminous and Nonluminous

The primary sources of light are bodies or substances that give off light of their own. They are called luminous bodies. Most important of these are the stars of our universe. The closest and most important star to us, of course, is our sun. Most other luminous sources of light are mere substitutes for the sun. For example:

Fuels such as wood, coal, gas, oil, candle wax, and matches give off or emit light when they produce a flame during burning. This is called combustion or rapid oxidation.

Gases such as neon and argon glow red and blue respectively when an electric current passes through each of them.

The tungsten filament (wire) in an electric light bulb becomes incandescent and glows white when electricity passes through it.

A fluorescent lamp glows when an electric current causes ultraviolet waves to be formed and to hit the inner coating of the tube.

The wires of electric toasters, ovens, and heaters glow red when electricity flows through them. They do not give much light, but it is their own.

Fireflies, "electric eels," and some fish glow by oxidizing certain chemicals called phosphors in their bodies.

Most objects in our environment are not luminous. If no light falls upon them, you cannot see them. In a totally dark room, you can see nothing. Using your memory of where furnishings are located, you grope for a source of light. You find and light a candle. Immediately, you see—but dimly—everything in the room. The faint glimmer of light restores your sight. The electric lights go on. Visibility returns slowly at first, then completely. The furnishings, walls, floor, ceiling, windows, and doors are now illuminated.

The planets and our moon are nonluminous. You see them only because they reflect the light they receive from the sun. We cannot see our own planet when we are on the ground. We see a limited section of it when we fly. When our astronauts circled the moon, however, they were able to see the planet earth because the sun's light was reflected from the earth's surface into their eyes.

What Is Light?

Light is a form of energy. It can stream out from a source and make things happen a distance away. It can do work. Light energy can be changed easily into other forms of energy. The following table summarizes some possible energy changes that can take place when light causes activity or work to be done.

Some Characteristics of Light

1. Light can travel through a vacuum. Not only through outer space, but here on earth, light can travel through a vacuum. This is easily seen by observing a radiometer. Most of the air inside the glass bulb has been removed. Now there is a partial vacuum. Within this vacuum, in the center of the bulb, is a set of vanes that can spin

Energy Change	*Activity or Work Done*
To mechanical energy	Spinning of a radiometer
To electrical energy	Operation of photoelectric cells and solar batteries
To heat energy	Process of combustion Process of evaporation Operation of solar heaters
To chemical energy	Photography Photosynthesis Color fading in fabrics Autumn color changing in leaves

easily. Allow the sun's light or light from a projector to shine on the radiometer. The vanes spin. Remove the light. The vanes stop spinning. Shine the light again. The vanes continue to spin as long as light falls on them. Light has traveled through a partial vacuum.

2. Light travels fast. The speed of light in a vacuum is 186,000 miles per second, or 300,000,000 meters per second. This has been proved experimentally a number of times. It is believed that the speed of light in a vacuum is the greatest speed that any form of matter or energy can have. It takes 8 minutes for sunlight to reach the earth and about 4 years for light from Proxima Centauri, our next nearest star, to reach us. The star is therefore said to be "four light years" away from us.

   In air, the speed of light is just slightly less than it is in a vacuum. In water, light travels three quarters as fast as in air, and in a diamond, it travels half as fast as it does in air.

3. Light usually travels in straight lines. If you flash a powerful searchlight across a darkened room, you can observe that the edges of that beam of light appear to be straight lines. You can assume that the entire beam is composed of innumerable imaginary straight lines of light. We call them rays. Observe a very narrow beam of sunlight entering a room between the window shade and the window wall. It also appears to be made of rays traveling in a straight line. If rays strike an object they cannot penetrate, they cannot curve around the corners of the object. They can only bounce back from the surface

on which they have fallen. That is why we cannot see around the corners of an opaque object. Later on we will explore the effect of this characteristic of light travel on the formation of images, shadows, and eclipses as well as on our general ability to see. In the early 1800's new experimental evidence caused scientists to revise some of their thinking on this subject and to favor a then newer, controversial theory of light.

4. Light responds to other materials. From experience, you know that different kinds of materials receive light from luminous objects differently. Opaque materials, such as blocks of wood, walls, floors, or books, stop light. Most of the light bounces back (is reflected) from the surface of these objects. Some of the light is absorbed as heat. You cannot see through opaque materials.

   Translucent materials such as waxed paper, tissue paper, and frosted glass allow some light to go through them. They transmit some light. The rest of the light is reflected. You cannot see objects clearly through translucent materials because they distort the light that passes through them. You can see hazy light and fuzzy outlines of objects through translucent materials.

   Transparent materials such as air, water, cellophane, and clear glass allow most of the light shining on them to go through. Some light is bounced back. These materials are light transmitters. You can see objects clearly through transparent materials.

   So it is that light from luminous objects can be absorbed (taken in), transmitted, and reflected by objects on which it falls. The extent to which light is absorbed, transmitted, or reflected depends upon the kind of object on which it falls.

Theories of Light

People have always wondered what light really is. In ancient times they thought it was a "feeler" sent out by their eyes. Later, people said that objects themselves sent out "something" the eyes could pick up. But no one could explain how they saw objects that did not send out their own light.

When we consider that about 85 percent of people's learning comes to them through their vision in response to light, it seems strange that it was not until the beginning of the 17th century that scientists began to try to explain what light is and why it behaves as it does. Scientists

performed many experiments with light. They formulated theories to try to explain what they observed. The first was called the corpuscular theory. This was soon followed by the wave theory. Later on, the electromagnetic theory was proposed. Lastly, the modern theory, the quantum theory came into being. Each theory tried to explain the discovered phenomena of the day and to predict new behavior patterns for light. Greater understanding of what light is and how it behaves led to the production of useful, practical applications. The presently accepted quantum theory combines some ideas of both early theories and adds other ideas. Let us examine each theory.

The Corpuscular Theory of Light

The great English scientist, Sir Isaac Newton, proposed the corpuscular theory early in the 17th century. He said that light was a stream of tiny particles or corpuscles shot off by luminous bodies. The corpuscles traveled in all directions in straight lines. They could enter transparent materials and were reflected from the surfaces of opaque materials. During reflection, the angle of reflection was always equal to the angle of approach or incidence. Soon controversy arose concerning the fundamental nature of light.

The Wave Theory of Light

In 1678 a Dutch scientist, Christian Huygens, proposed a new theory of light. He said that light is composed of a series of waves that spread

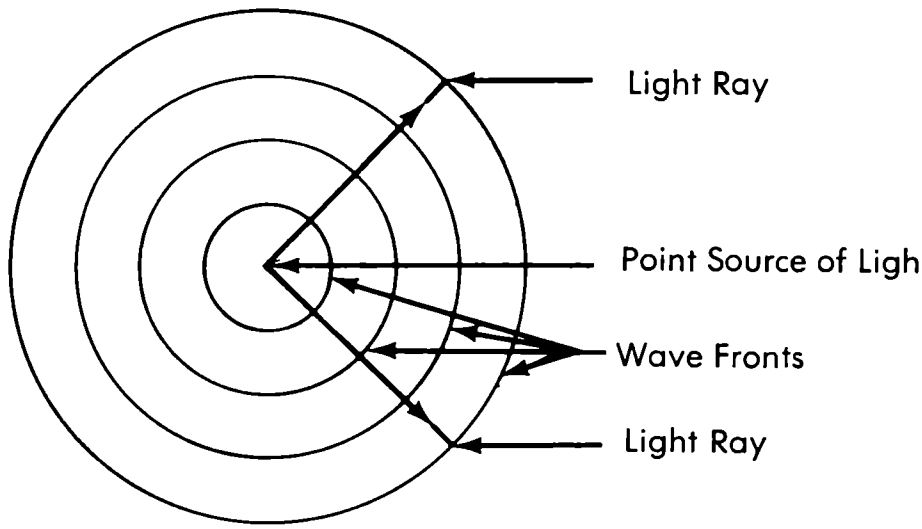

FIG. 1 *Concentric waves.*

out from a light source in all directions. A wave is a vibrating motion that travels along. The concentric circular waves produced by every light source are very much like the waves produced when a pebble is dropped into a pool of water. The crests of the waves are called wave fronts. Each radius of those wave fronts is called a ray. The rays travel in a straight line while in any one substance such as air alone or glass alone. When these waves meet other substances or objects, some of them are turned back or reflected in such a way that the angle of reflection of any ray is equal to its angle of incidence.

Both the corpuscular theory and the wave theory offered good explanations for: (1) the reflection of light; and (2) the traveling of light rays in straight lines. However, the wave theory could better explain newly demonstrated facts about light such as interference, diffraction, and polarization.

Interference results when two light beams from the same source come together. At certain points, they reinforce each other (add up) to produce extra brightness. At other points, they may cancel each other to produce darkness. It was argued that to do this, light must be made of waves.

Diffraction is the slight bending of light away from the straight line when it passes the edge of an object in its path. This bending is so slight that it went unnoticed. Only waves can diffract. Particles cannot. This supported the wave theory.

Polarization is the result of passing light through a crystalline or polaroid filter. Only the part of light that vibrates parallel with the plane of the filter will pass through it. Vibrations of light in any other direction are eliminated. Sound waves that are longitudinal could not be polarized. Only light waves could be polarized. This fact showed that light waves must be transverse (crosswise), with vibrations at right angles to the direction in which the waves are moving. Polarization eliminates all vibrations except those that happen to be lined up with the plane of the polarizer. Particles could not be polarized. Only waves could. Therefore, this observed ability of light supported the wave theory of light.

The Electromagnetic Theory of Light

In the 19th century a British scientist, James Clerk Maxwell, refined the wave theory by proposing the electromagnetic theory of light. He

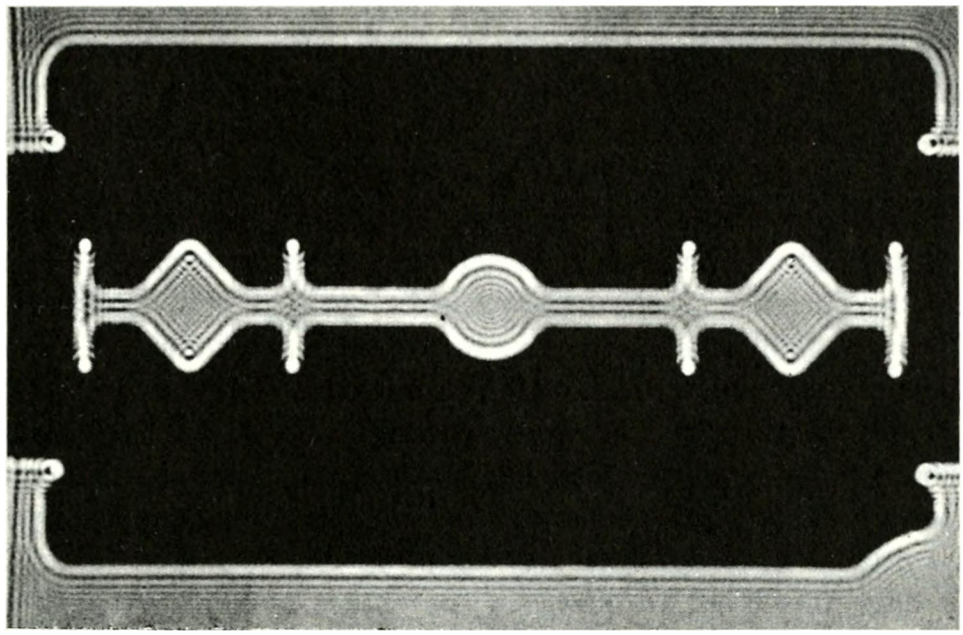

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FIG. 2 *Bright and dark bands—diffraction and interference (from Richards, Sears, Wehr, & Zemansky,* Modern College Physics).

said that light waves are the visible part of a whole group of waves he called electromagnetic. They consist of electric and magnetic vibrations at right angles to the direction in which the waves are moving. Electromagnetic waves vary in wavelength from the longest radio waves to the shortest gamma rays, with infrared, light, ultraviolet, and X-rays in between. Light waves have different wavelengths expressed as different colors. All electromagnetic waves travel at the speed of light and exhibit most of the properties of light. More about this later.

The Quantum Theory of Light

By the dawn of the 20th century new discoveries about the behavior of light suggested that at times light really behaves more like corpuscles than like waves. This led Max Planck, Albert Einstein, and other scientists to introduce a new form of the corpuscular theory of light, which they called the quantum theory of light. According to this theory, light is emitted from a source in tiny, separate (discrete) bundles of energy. These bundles of energy are called quanta or photons. Each photon possesses a fixed quantity of energy so small that if it bumps into an

electron, it can be absorbed by that single electron. Photons behave like particles when they bump into very small bodies. The color of a photon of light is determined by the energy it possesses.

Photons of the quantum theory are bundles of energy. The particles of the corpuscular theory were thought of as bullets of material shot off by luminous bodies. Nevertheless, the modern quantum theory uses the particle idea to explain such activities as the changing of light to an electric current in a photoelectric cell often called the "electric eye."

Of course, light still behaves like waves in many instances. To explain these wavelike characteristics, the quantum theory assumes that photons are guided in paths through space or matter by waves. This makes it possible to explain interference, diffraction, and polarization. Therefore, the particle theory and the wave theory of light complement each other in the present quantum theory of light.

To date, this is all we know of the nature of light. Perhaps some day you will add to our understanding of the "true" nature of light.

SUMMARY

Sources of Light

An object is seen by the light it sends out.

Luminous bodies emit their own light. The stars, our sun, and substitute lights are luminous bodies.

Illuminated bodies have no light of their own. They are nonluminous. They are seen by the light they reflect. Most objects in our environment are nonluminous. They reflect light that falls on them.

The Nature of Light

The sun is the main source of all light and energy.

Light is a form of energy that travels as electromagnetic waves.

Light travels in a vacuum at the speed of 186,000 miles per second or 300 million meters per second.

Light travels in paths that are usually straight lines, but it bends ever so slightly around the edges of obstacles in its path. This bending is called diffraction.

Light can be reflected, absorbed, or transmitted depending upon the

kind of material it shines upon. When light is reflected, it bounces back so that it leaves the surface of the object at the same angle (or slant), called the angle of reflection, as it approached the surface, called the angle of incidence.

Transparent objects allow most of the light to pass through (be transmitted). Some light is absorbed and some is reflected.

Translucent objects allow only some light to pass through. Most is reflected. Some is absorbed.

Opaque objects stop light and cause it to be reflected. Some light is absorbed as heat.

Theories of Light

A theory attempts to explain scientific observations and to predict others. New evidence, properly tested, may cause scientists to revise a previously accepted theory. So it was with theories of light.

According to the corpuscular theory, light is made up of tiny particles shot out of luminous bodies.

According to the wave theory together with the electromagnetic theory of light, light consists of transverse electromagnetic waves that radiate from luminous bodies. It explains the observed behaviors of light called interference, diffraction, and polarization. It cannot explain light's ability to be absorbed by electrons and so change to electrical energy.

The quantum theory combines features of the corpuscular and the wave theories to explain observed behavior of light. According to the quantum theory, light consists of bundles of energy called photons, which behave at times like particles. Photons travel along paths determined by electromagnetic waves.

II

Shadows and Reflections

Shadows and reflections: What have they in common? Of course! Each can be formed because light rays usually travel in straight lines as long as they remain in the same medium or in a vacuum. Let us first explore the formation of shadows.

Ordinary Shadows in Our Lives

Whenever light rays strike an opaque object, they can travel no farther. They stop, and the opaque object casts behind itself a dark upright image called a shadow. The shadow falls on the side opposite the light source. Shadows vary in size and intensity.

Try these experiments to discover how shadows vary.

1. Cover an electric lamp with a box in which a very small hole has been made. Place this apparatus about 2 feet from a screen or a white wall. Shine the beam of light from this "point source" (tiny source) onto the wall. Hold an object such as a spoon in the path of the light beam but close enough to the wall to obtain a clear shadow. Observe the totally dark shadow on the wall. It is called an umbra. Move the spoon, still in the path of the light beam, toward the light source. What happens to the size of the shadow on the wall? Observe that the closer the object comes to the light source, the larger its shadow becomes.
2. Remove the cover from the electric lamp. Now you have a relatively large source of light. Shine it on the wall. Hold the spoon in the path of the light beam, once again, as near the wall as necessary. What do you see?

   You have observed that a large source of light produces an inner

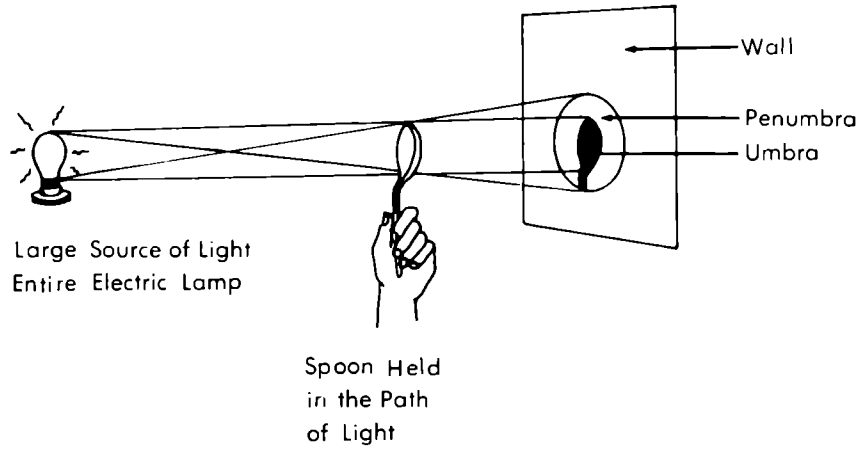

FIG. 3 *Umbra and penumbra.*

sharp dark shadow, called an umbra, and an outer fuzzy grayish shadow, called a penumbra. All points in the umbra are in total darkness because they receive no light rays from the source of light. All points in the penumbra are only in partial darkness (gray) because they do receive light rays from some parts of the light source but not from the central part.

3. Repeat these experiments using a large serving spoon and small iced-tea spoon. Variation here is to be in size only. What do you observe? A larger object produces a large shadow; a smaller object, a smaller shadow.

Now let us consider the effect of the sun on shadow formation. Our sun sends rays to the earth and to the other heavenly bodies of our solar system. Because the sun is so distant (93 million miles away), it produces shadow effects on earth as if it were a point source of light. The shadows are sharp and dark. You may have seen the sharp dark shadow of an airplane moving on the ground of an airfield as the plane prepares for takeoff. You may have seen the shadow of a cloud on a mountainside; of trees, buildings, poles, and people elsewhere. Young children try to catch their shadows. Why must they be frustrated? Read on . . .

One sunny summer morning, as John was walking to the playground, he saw his shadow. He tried to catch it, but as his body moved, his shadow moved along with him. At noon, with the sun directly overhead, John observed that he had practically no shadow at all. Was it lost?

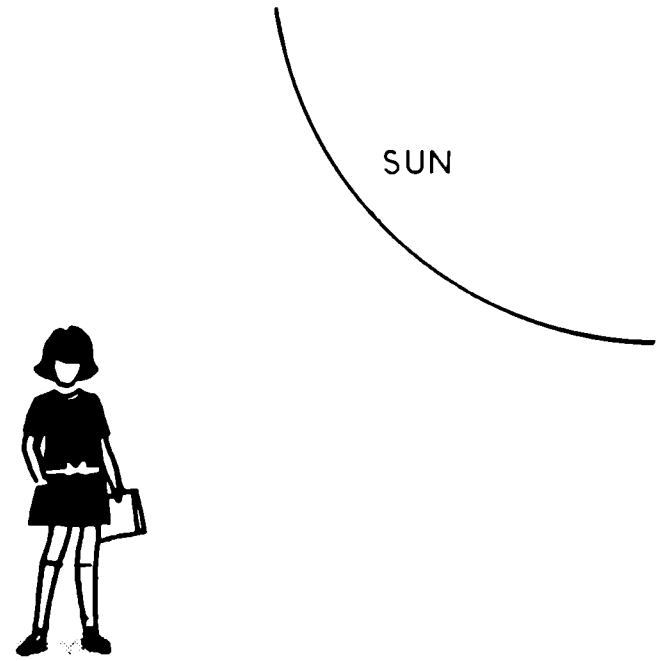

FIG. 4 *Early morning shadow.*

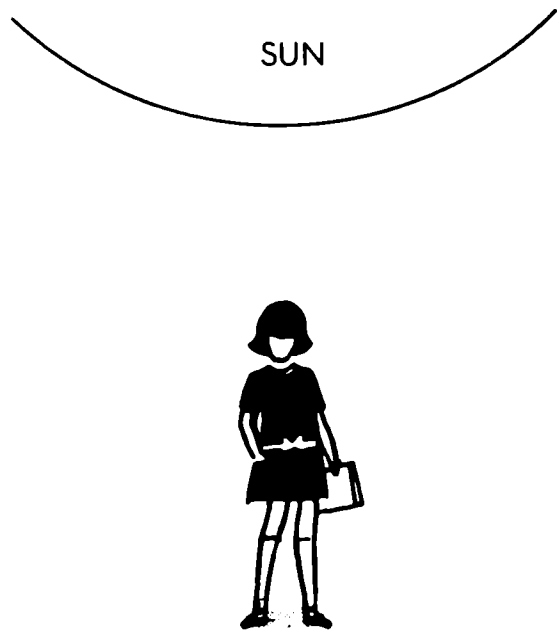

FIG. 5 *Midday shadow.*

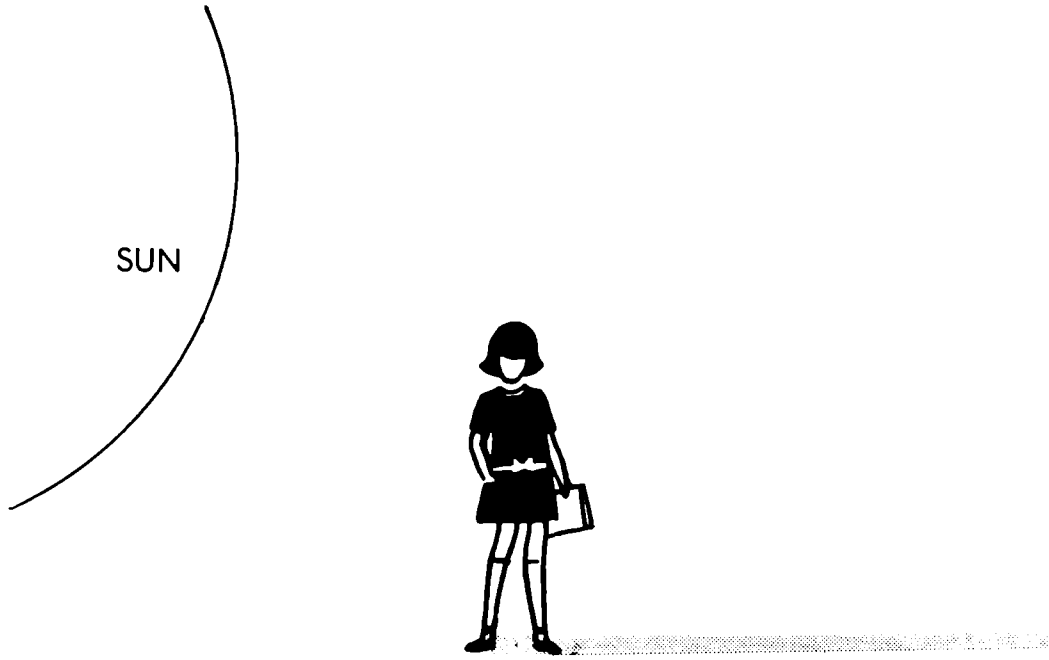

FIG. 6 *Late afternoon shadow.*

No. It could scarcely have been formed because the light rays beat directly down upon him and there was no space opposite his vertical body for a shadow to be formed. As the afternoon wore on, he started to walk home. The sun was low in the sky, and the rays were deeply slanted. How tall his shadow looked to him now! If only he could capture it. Night came. The sun's rays were shining on the side of the earth opposite where John lived. The region where John lived was facing the earth's shadow. As the earth continued to rotate on its axis, John's region would leave the darkness of the earth's shadow and enter the brightness of a new day.

Eclipses

The shadows of heavenly bodies cause eclipses. The word "eclipse" means "the partial or complete obscuring (hiding, concealing), relative to a designated observer, of one celestial (heavenly) body by another."

Eclipse of the Sun

An eclipse of the sun, or solar eclipse, occurs when the moon moves into a position directly between the sun and the earth, cutting off some

of the sun's light to the earth. The moon's shadow then falls on the earth, forming both an umbra and a penumbra. People living where the umbra falls, a strip less than 100 miles wide, experience a total eclipse. They cannot see the sun. Its rays are obscured to the observer's view by the moon. The region is temporarily in total darkness. People living on the part of the earth where the penumbra falls experience a

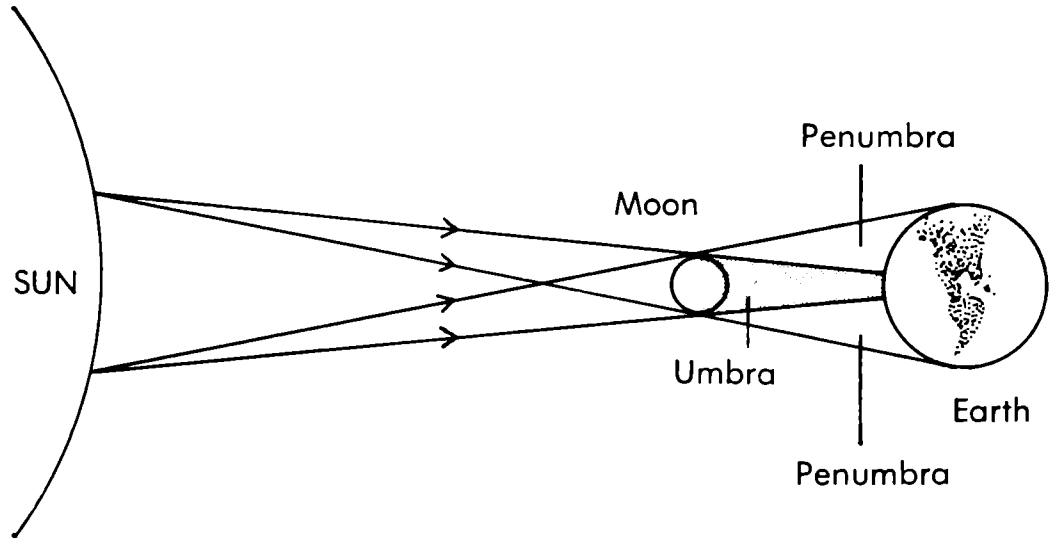

FIG. 7 *Solar eclipse.*

partial eclipse. Only part of the sun's disc is obscured to the observer's view by the moon. This region is temporarily in partial darkness. Some of the sun's light passes by the moon, reaching the earth in this region. Total solar eclipses are very rare.

Eclipse of the Moon

Unlike total solar eclipses, lunar eclipses occur fairly frequently. An eclipse of the moon occurs when the earth moves into a position directly between the sun and the moon. People living in the region of a lunar eclipse can watch the moon move first into the penumbra and then into the umbra of the earth's shadow, where the moon is temporarily in complete darkness. Deprived of the sun's rays, the moon has no light rays to reflect to us; therefore, it cannot be seen until it moves out of the umbra into the penumbra on the side opposite the one where it originally entered into the earth's shadow.

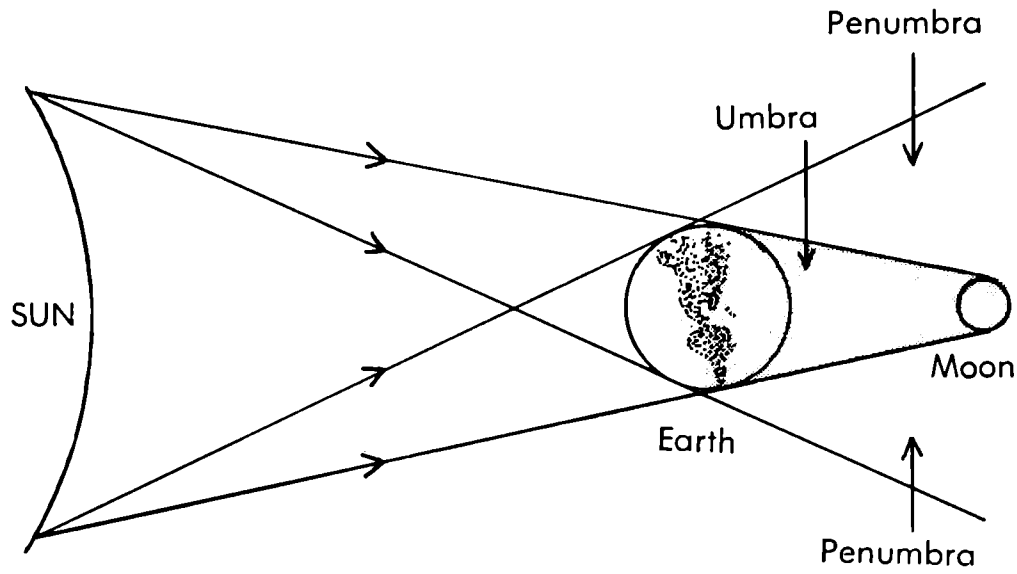

FIG. 8 *Lunar eclipse.*

Reflection of Light

Reflection of light refers to the turning back of some rays of light after they strike a surface. The kind of light reflection that takes place depends upon the kind of surface the light rays strike.

Regular and Diffuse Reflection

When light beams strike a smooth, flat, still, shiny surface, such as a mirror or a still body of water, the parallel incoming rays (incident rays) bounce back as parallel reflected rays. This is called regular reflection or glare. The order of incident rays has been reversed on reflection. This explains why an image is reversed in a mirror.

However, most surfaces, such as walls, pages of books, or the skin of living things, are not smooth; nor are they polished. Their surfaces consist of many microscopic irregularities and projections. Each incident ray strikes a different part of these rough spots. Since each ray is reflected according to the Law of Reflection, each is reflected in a different direction. Thus the reflected rays are scattered. This is called diffuse reflection and is relatively free of glare.

Discover the Law of Reflection for yourself. Place a flat mirror (called a plane mirror) upright against a flat surface in a dark room. Your

dresser, desk, or table will do. Place a large sheet of white paper on the flat surface. Shine a very narrow flashlight beam straight ahead, at right angles to the mirror. The rays of this beam will be reflected directly back toward the flashlight. This is called the normal ray or just the normal. Using a ruler and sharp pencil point, draw the normal on the paper. Label this line AB. Now bring the light to the left (point C) and shine it so that it hits point B. What do you observe? Of course,

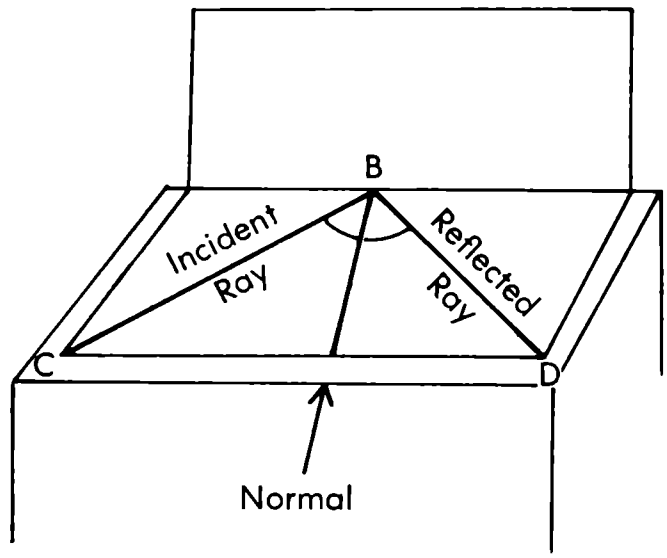

FIG. 9 *Law of reflection.*

the reflected ray emerges on the side opposite the incoming ray. Carefully draw the line CB (the incident ray) and line DB (the reflected ray). Using a protractor, measure angle CBA. This is the angle of incidence. Now measure angle DBA. This is the angle of reflection. How do the two angles compare? Select other points from which to send incident rays. What do you find to be true?

Yes. The angle of incidence equals the angle of reflection. This is called the Law of Reflection, which says that no matter how light strikes a reflecting surface, it rebounds from that surface so that the angle of incidence equals the angle of reflection. In addition, the incident rays, the normal, and the reflected ray all lie in the same plane (on the same surface).

How Mirrors Are Made

Artificial mirrors are the best reflectors of light rays. They are made of clear, transparent glass backed by a silvery compound and coated

on the rear surface with black paint. The finer the quality of glass used and the more skillful the application of the backing materials, the better will be the clarity of the reflections produced by the mirror. You have undoubtedly observed that windows, transparent by day, become mirrors at night when the house is lighted and darkness backs up the window. If you care to look out, you will see your reflection. Any smooth, shiny surface, even very still water, can function as a mirror.

Kinds of Mirrors

Classified according to shape of surface, there are three kinds of mirrors: plane, concave, and convex.

A *plane* mirror has a flat surface. Have you ever used one to catch the sun's rays and have them reflect as a bright spot on a ceiling or wall? If so, you discovered that by tilting the mirror in various directions, you could direct the spot wherever you wished it to go. A word of caution: NEVER DIRECT THE SPOT TOWARD YOUR EYES. THE GLARE WILL HARM YOUR EYES.

You can discover the characteristics of images made in plane mirrors by making some careful observations. Stand about 2 feet in front of a full-length mirror alongside of which you have hung a tape measure. Your image is standing upright. How does your height compare with the height of your image? Pretty much the same. Take a giant step backward. What does your image do? It appears to move as far back from the surface of the mirror as you have really moved back from it into the room. Step forward. What happens? Yes, your image seems to be as far behind the mirror as you are in front of it. Is your image really "in the mirror," as we so often say? No. Actually, there is nothing behind the mirror. You see yourself when the light rays come to your eyes after they have been reflected from the mirror. You only think they came from the image behind it. Since no light falls where the image seems to be located, the image cannot be captured on a screen or projected onto a screen. It can only be seen by looking in the mirror. Such kind of image is called a *virtual image.*

Hold up some printed matter so that you can see it in the mirror. The image is reversed from left to right. When you look at yourself in the mirror, your face and body are reversed in the same way.

"If we could but see ourselves as others see us." But we can't. Now imagine yourself standing where your image appears to be. Touch your

left ear. Your image is touching its right ear. Pretend to write. If you are right-handed, you will appear to be writing left-handedly. To understand why all this is so, remember what we said before: the order of reflected rays is the reverse of the order of incident rays.

Would you like to reverse your image again? Place two plane mirrors at right angles to each other. Place yourself so that you see one half

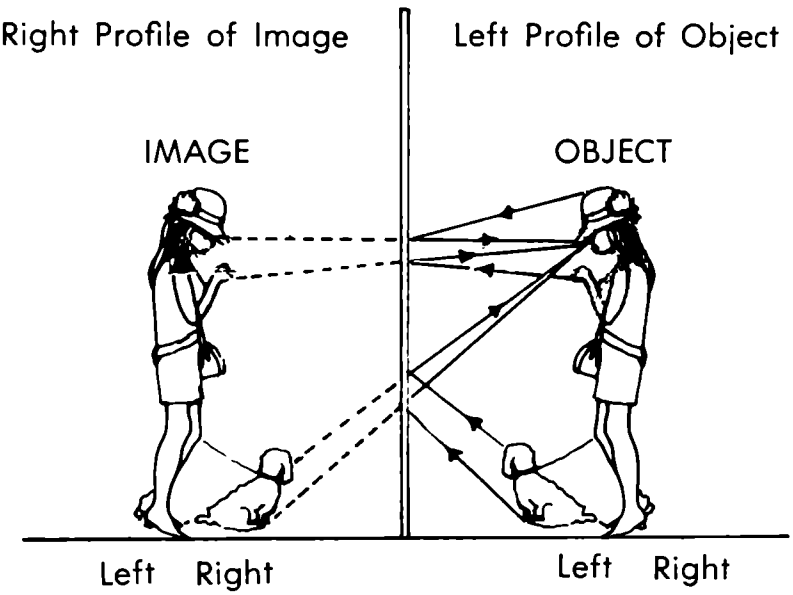

FIG. 10 *Image in a plane mirror.*

of your face on each side of the mid-line where the two mirrors touch. Again, touch your left ear. Your image touches the other ear, which turns out to be your left ear!

A very interesting and useful device can be created by laying a third flat mirror on the table between the two standing ones. This is called a *corner reflector.* As long as you remain in front of this device, you can see your image in it from any position in the room. Small wonder that corner reflectors are used in preceremonial bridal dressing rooms. They are also used in space satellites, where they reflect light and radar signals back to earth.

Plane mirrors are used to view ourselves and for many other purposes. They can be hung on walls in such a way that they create the illusion of a larger room. The rear-view mirror of a car is a plane mirror that allows the driver to see the road behind the car. Periscopes are devices using plane mirrors to change the direction of light rays so that the viewer can see above his head from a concealed position. Submarines,

armored tanks, and space capsules have periscopes. Sextants are used by navigators to determine the ship's position when at sea and to help plot its course. Light from the sun or a star is reflected from two mirrors on the sextant. The angle the mirrors make is used to calculate the ship's position.

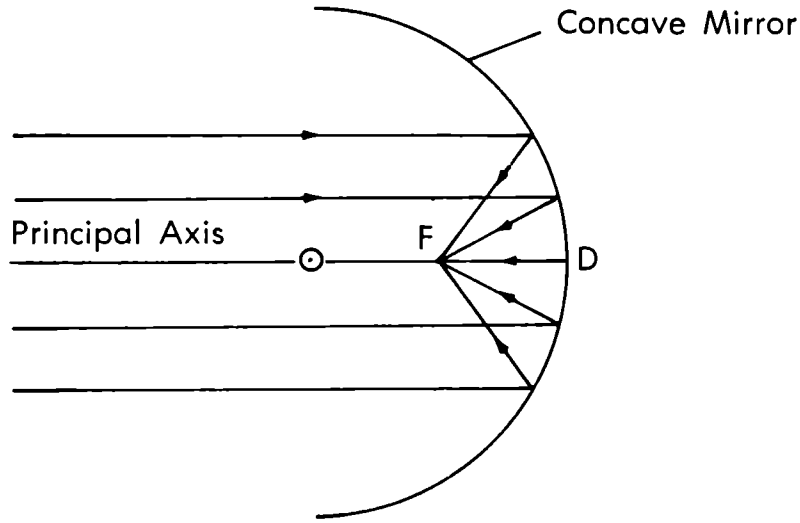

FIG. 11 *Converging action of a concave mirror.*

A *concave* mirror has a surface that curves inward. It has many uses. It can form virtual images and real images. The virtual images appear erect and enlarged, such as those formed by a shaving mirror when we use it to view our faces. The real images come out inverted and vary in size according to the distance of the object from the mirror.

To discover how a real image is formed, use a shaving mirror as a scientific instrument. Turn it toward a shining lamp. Move a large card back and forth in front of the mirror until you see a sharp image of the lamp. It will be real, the result of converging rays of light. It will be inverted and reversed from side to side. This concave mirror can be used to focus the sun's rays on a card or screen, making a real image of the sun itself. BE CAREFUL. Do not look into the mirror. To do so is just as dangerous as looking directly at the sun. Hold a card a few feet away from the mirror and discover the brilliant spot of light on the card. Shortly, the sun's rays will cause the card

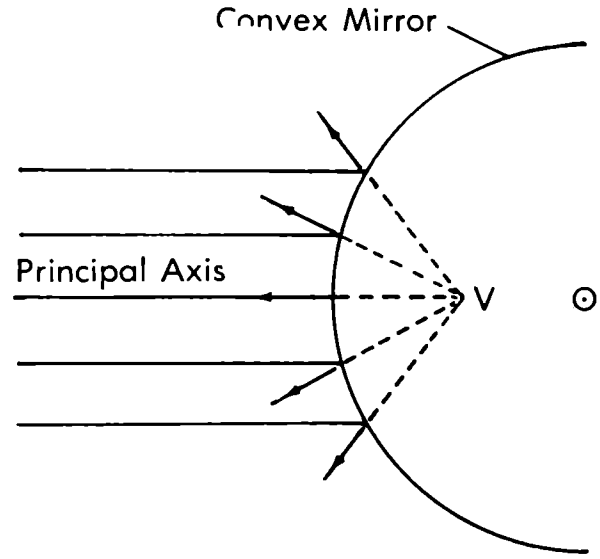

FIG. 12 *Diverging action of a convex mirror.*

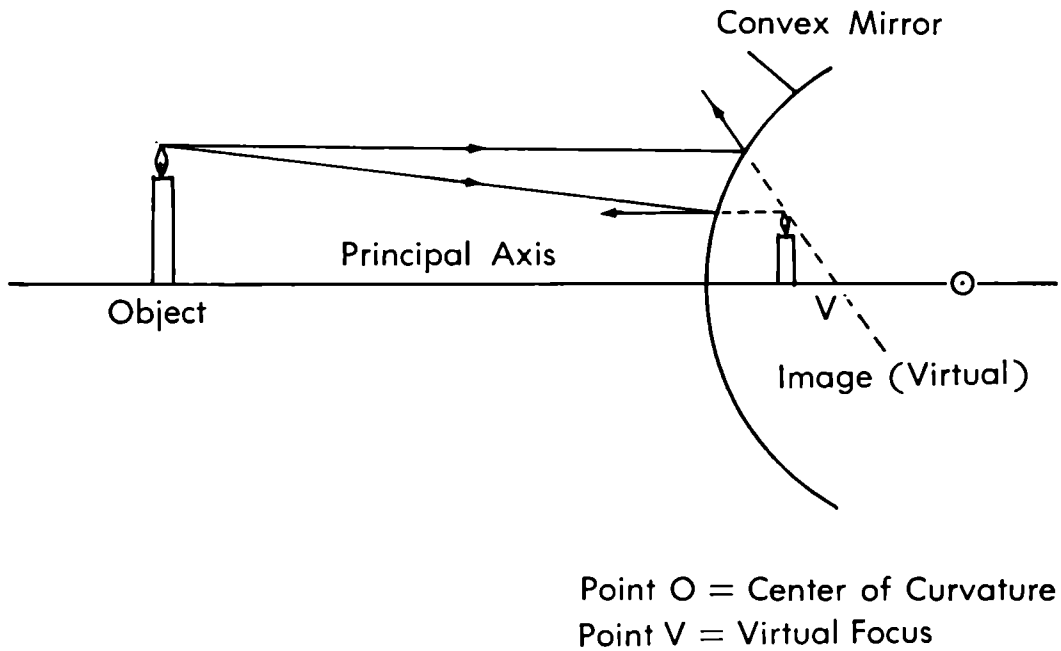

FIG. 13 *Image formation with a convex mirror.*

to smoke and char. Discontinue this activity. After all, the ancient Greek scientist Archimedes is supposed to have set enemy ships afire by using sunlight and concave mirrors. Today, this technique is used in solar furnaces.

Concave mirrors are used in flashlights and auto headlights. They are used in reflecting telescopes to gather light from distant skies, making it possible sometimes to discover the presence of faint distant stars. Concave mirrors are also used in radar (radio detection and range finding), to detect radio waves by which planes, ships, and weather conditions can be detected.

A *convex* mirror has a surface that curves outward. It causes parallel incident rays to diverge (spread out) when they are reflected from its surface.

What kind of image does a convex mirror form? The image is always erect, smaller than the object, and virtual (not real).

Convex mirrors are used as side-view mirrors on trucks and cars, as mirrors inside elevators, and as divergent mirrors to observe customer behavior in stores and banks.

SUMMARY

Shadows and reflections are possible because light rays usually travel in a straight line through a single medium or a vacuum.

Shadows

A shadow is a dark image cast by an opaque body in the space behind itself when that object blocks light rays falling on it.

A shadow has the same shape as the object that casts it.

The size of the shadow depends upon the size of the object and its distance from the light source.

The closer an opaque object is to the light source, the larger is its shadow.

The length of a shadow made in the path of the sun's rays varies with the time of day. The lower the sun is in the sky, the longer the shadow formed. When the sun is directly overhead, no shadow is seen.

The sun is so far away from the earth that it is considered to be a point source of light.

When the source of light is larger than the object in the path of its rays, a two-part shadow is formed. The inner sharp dark part where all rays have been blocked by the object is called the *umbra.* The outer fuzzy grayish part where some outer rays have fallen is called the *penumbra.*

Shadows of heavenly bodies cause eclipses.

A solar eclipse occurs when the moon is directly between the sun and the earth. Total solar eclipses are rare in any locality on earth.

A lunar eclipse occurs when the earth is directly between the sun and the moon. This occurs frequently.

Reflections

Reflection of light occurs when light rays strike a surface and are bounced back.

The Law of Reflection says that when a light ray strikes a surface,

Mirrors as Reflectors

Kind of Mirror	*Kind of Image*	*Uses of Mirror*
Plane	Virtual Erect Same size as object Reversed As far behind the mirror as the object is in front of it	For self-inspection To create illusion of space As rear-view mirror in cars In periscopes and sextants In corner mirror setups
Concave	Virtual Erect Enlarged or Real Inverted Vary in size	Shaving mirror Flashlights, headlights Radar Solar furnace Reflecting telescope
Convex	Virtual Erect Smaller than object	As side-view mirrors in cars As mirrors in elevators To observe customer activities

it is reflected so that the angle of incidence (approach) equals the angle of reflection (bounce back).

Regular reflection from smooth shiny surfaces causes glare. Parallel incident rays bounce back as parallel reflected rays with their order reversed.

Diffuse reflection occurs when parallel incident rays strike rough surfaces and bounce back according to the Law of Reflection. The reflected rays are scattered in different directions, reducing glare.

There are three kinds of mirrors based on shape of surface. They are: concave (surface curved inward), convex (surface curved outward), and plane (surface flat).

III

Diffraction and Refraction

Diffraction and refraction both refer to the bending of light. How do they differ?

Diffraction

Diffraction is the slight bending of light away from its straight line of travel when it passes the edge of an object in its path. This bending is so slight that it went almost unnoticed during Newton's time.

About 1650, however, Francesco Maria Grimaldi, an Italian scientist, questioned the then-prevalent idea that light travels in straight lines and causes objects in its path to cast sharp shadows. He said that if the edges of a shadow were examined closely, they would prove to be slightly blurred; that light does bend around obstacles, if only slightly. He suggested that since light has such short wavelength, bending could be observed only when light waves pass through very small openings. He set up experiments to test his ideas. He let sunlight come through a very small hole in a card and used it to look carefully at the shadow of a metal rod. Indeed, this shadow had fuzzy edges. In another experiment, he observed that when a very small object was placed between a point source of light and a screen, the shadow of the object was slightly smaller than would be expected if light rays passed the object in straight lines. To Grimaldi, this observation suggested that light must be bending around the edges of the object, thereby reducing the size of its shadow slightly. Another experiment was performed. He allowed light from a point source to pass through a pinhole and fall on a screen. He observed that the bright spot on the screen was larger than could be expected if light travels only in straight lines. This showed that light did bend around the edges of the hole, thereby increasing slightly the size of the light spot on the screen.

Grimaldi recognized that light did bend away from a straight-line path, but he could not fully explain why. Surely this bending was different from the bending called refraction, which involves two media (different substances). Therefore, Grimaldi gave this newly recognized bending of light a new name. He called it diffraction.

An understanding of diffraction did not come until about 150 years later, when the wave theory of light emerged to explain this and other phenomena.

Would you like to observe diffraction? Hold a finely woven cloth or fine wire mesh up to your eyes and look through it at a large, distant source of light such as a street lamp. Light comes through the tiny openings between the threads of material or metal mesh and spreads out to form a configuration that you recognize as a cross. If you turn the material or mesh to the right and around in a circle, you will observe that the cross also turns. Since the source of light is not turning, the cross pattern must be the result of the bending of light itself as it passes through the tiny openings of the material.

Diffraction Gratings

Diffraction is used to sort out different wavelengths in a beam of light. If the beam is sent through a narrow slit, the long waves spread out more than the short ones. If the different wavelengths are to be separated more precisely, we must use an instrument having many slits placed closely side by side. This instrument is called a diffraction grating. It is a piece of transparent material with as many as 10,000 parallel, equally spaced, opaque lines etched in a space 1 centimeter wide. When light shines on a diffraction grating, each smooth, transparent space acts like a tiny slit. As light passes through a slit, it is diffracted and spreads out. Light spreading from one slit may interfere with light coming from other slits, thereby producing a diffraction pattern. Diffraction gratings can be used to determine the wavelength of light very accurately. Gratings ruled with more than 250,000 lines per inch are used to diffract X-rays.

Crystals such as quartz are natural diffraction gratings whose atoms are evenly spaced in three dimensions. The spacing is small enough to diffract X-rays. Crystals make spot patterns. Scientists learned to use the spot pattern measurements to figure out the wavelength of X-rays. Chemists, in turn, use X-ray diffraction to photograph and study

the spot patterns of other crystals in order to learn how the atoms in those crystals are spaced. This, along with other information, gives scientists an idea of the properties of the materials studied. This technique helped scientists select appropriate heat-resistant materials for use in the nose cones of rockets, in jet engines, and in nuclear reactors.

An especially exciting use was made of X-ray diffraction in the 1950's to help solve the mystery of the molecular structure of DNA deoxyribonucleic acid. The English scientist Maurice F. H. Wilkins and his colleagues at Kings College, London, took pictures of the X-ray diffraction patterns made by DNA. These they studied, analyzed, and interpreted. This work, together with experimental evidence gathered through the chemical analysis of DNA and other scientific investigations, led James D. Watson and Francis H. Crick to suggest a "model" of the structure of the DNA molecule. For this work, these three men, Watson, Crick, and Wilkins, shared the Nobel Prize in 1962.

Diffraction and Resolving Power

We already know that the ratio (relationship) of the width of an opening through which light passes to the wavelength of the light passing through it determines the size of the diffraction pattern produced by the slit or opening. If the ratio is large, the diffraction pattern will be small. If the ratio is smaller, the diffraction pattern will be larger. Grimaldi demonstrated this.

This is also true of optical instruments in which light must pass through one or more lenses. The larger the ratio of the diameter of a lens to the wavelength of light passing through, the smaller the diffraction pattern produced. The smaller this ratio, the larger and more spread out will be the diffraction pattern.

The resolving power of an optical instrument (its lenses and mirrors) is its ability to produce clearly distinguishable images of two objects that are very close together. To increase resolving power, reduce the diffraction effects.

Example 1. Suppose we look through a telescope at two stars that are close to each other in the sky. If the objective lens has a small diameter, the diffraction pattern of each star will be large and their images will overlap. If we use an objective lens of sufficiently larger diameter, the size of the diffraction images will decrease, there will be no overlapping, and the resolving power of the telescope will have been increased.

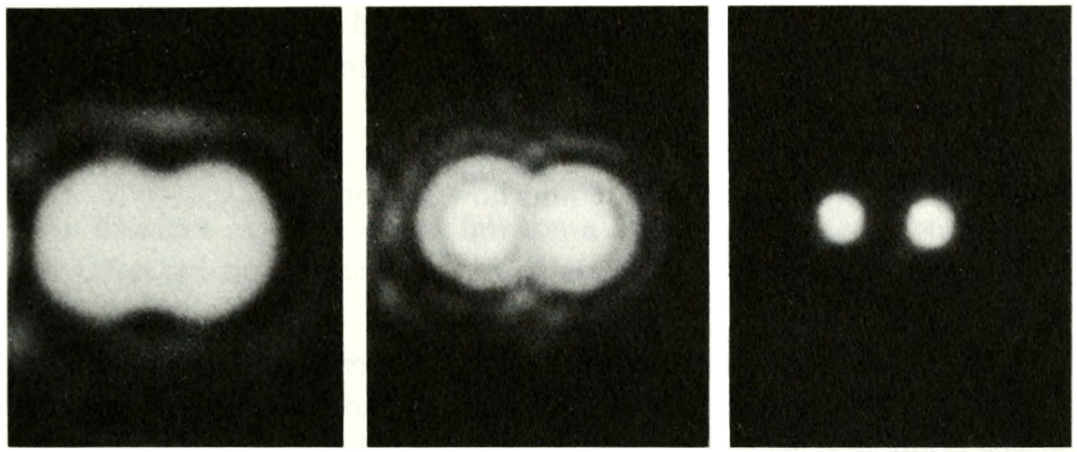

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FIG. 14 *Resolving power of a telescope (from Sears & Zemansky,* University Physics, *3d ed.).*

Example 2. Remember that a ratio is a relationship. In microscopes, the diameter of the objective lens is small. When a scientist must use high power, diffraction effects may make it difficult for him to distinguish clearly neighboring structures he wishes to study. In some laboratories, light of a shorter wavelength is provided—blue or violet. This increases the ratio of lens diameter to wavelength of light, thereby increasing the resolving power of the microscope by decreasing the diffraction effects of the lens.

Refraction

Have you ever observed any of the following phenomena? If so, you have seen refraction at work.

Early in the morning, the glow of sunlight is visible on the horizon before sunrise.

The sun's rays and glow are visible for a few minutes after the sun has set beneath the horizon.

On a clear night, the stars twinkle.

As you ride along on a hot pavement on a bright, hot, sunny day, you suddenly "see a pool of water" some distance ahead.

When rowing, as you dip the oars into the water, the submerged portions appear to have broken off from the main shaft and lifted up in the water.

When your friend is emerging from a dip in the pool, his head

and shoulders seem momentarily disconnected and out of alignment.

When you spot a beautiful stone in a stream and reach for it, it is not where you thought you saw it.

There are many similar observations you might have made. Let us now find out what refraction is and how it works.

Some Definitions

Refraction is the bending of a light ray as it passes at an angle (obliquely) from one transparent medium to another. Refraction occurs at the boundary between two media.

Try this: Fill a large glass bowl with water to within two inches of

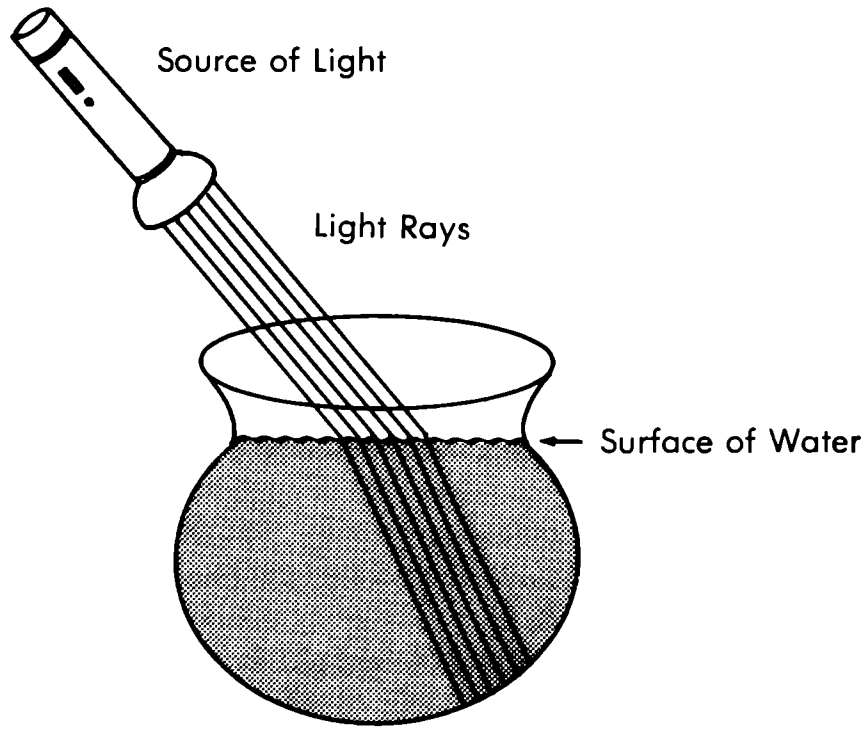


FIG. 15 *Light enters water obliquely.*

the top. Color the water slightly with red ink to make it more easily visible. Mask the face of a flashlight so that it will emit a very thin beam of light. Darken the room. Shine the light straight down into the water so that the rays enter the surface of the water at right angles to it. Does the light bend? Is it refracted? No—not under these circumstances.

Now slant the flashlight and shine the light so that it enters the

surface of the water at an angle. What happens to the light rays? Now the light rays are bent (refracted) as they enter the surface of the water.

Further Definitions (see the diagrams)

An incident ray is one that falls on a boundary between two media.

A refracted ray is one that has entered a new (second) medium and and is bent.

The normal is the line at right angles (perpendicular) to the surface between the two media.

The angle of incidence is the angle formed by the incident ray and the normal.

The angle of refraction is the angle formed by the refracted ray and the same normal.

How and Why Does Refraction Occur?

Examine the following chart. Note the speed of light in each of the media listed.

Medium	*Speed of Light*
Vacuum	186,000 mi/sec.
Air	186,000 mi/sec.
Water	140,000 mi/sec.
Glass	124,000 mi/sec.

Because the speed of light in water is less than in air, we say that water has a greater *optical density* than air. The optical density of air is less than that of water. When light strikes the surface of a new transparent medium, some of the light is reflected and some enters the new medium. The rays that enter the new medium are bent in a special way, obeying the Laws of Refraction.

Laws of Refraction

1. When a light ray enters a new medium at right angles to the surface of the medium, it is not refracted. It does not change its direction.
2. When a light ray passes obliquely (on a slant) from a medium of

LAWS OF REFRACTION

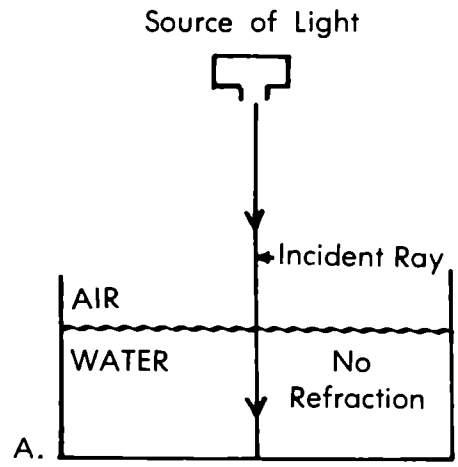


FIG. 16 *Perpendicular entry of light from air into water.*

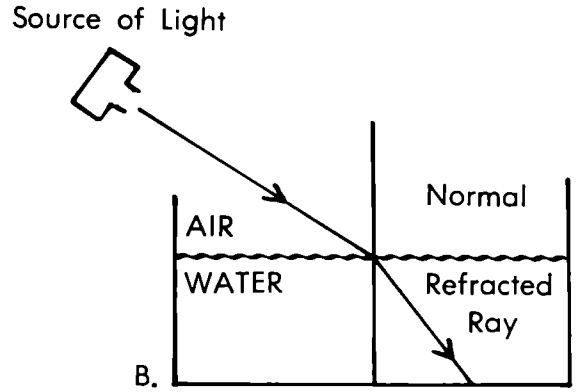


FIG. 17 *Oblique entry of light from air into water.*

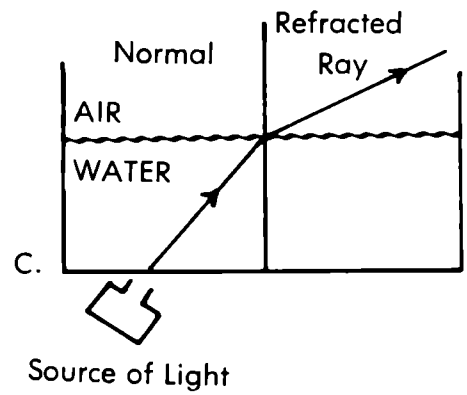


FIG. 18 *Oblique entry of light from water into air.*

lower optical density to one of higher optical density, it is refracted toward the normal. Example: air to water.

3. When a light ray passes obliquely from a medium of higher optical density to one of lower optical density, it is refracted away from the normal. Example: water to air.

Index of Refraction

The index of refraction of a substance is the ratio of the speed of light in a vacuum (or air) to the speed of light in that substance. The higher the index, the more the light will be slowed down as it passes from a vacuum (or air) into the second medium. (Note that the plural of index is indices.)

Indices of Refraction

Medium	*Index*
Vacuum	1.00
Air	1.00+
Quartz	1.33
Glass	1.50—1.90
Diamond	2.42

Refraction as a Detective

1. The difference between butter and margarine can be detected by the way these particles refract light.
2. True diamonds refract light more strongly than almost any other transparent material. They sparkle characteristically. Synthetic diamonds refract light differently. They can be detected.

Sunrise, Sunset

The earth's atmosphere refracts light. This enables you to see the sun for a few minutes before it rises above the horizon at sunrise and after it sinks beneath the horizon at sunset. At those times, the angle of incidence of the sun's rays relative to our atmosphere is greatest. Our atmosphere spreads this light by refraction and diffusion. (More later.)

Stars Twinkle

Stars seem to twinkle because the moving masses of the earth's atmosphere, varying in temperature and density, continually bend the star's light from side to side. Celestial observation requires clarity of vision. It is best done on cold, clear, winter nights high in the mountains. That is why astronomical observatories are located on mountain tops. In recent years, telescopes have been put in orbit in space labs so that they can photograph heavenly bodies free of atmospheric interference.

Mirages

A mirage is a phenomenon in which the refraction of light rays makes us think water is where it is not. For example, on a hot day the air directly above a pavement is much hotter than air higher up. As a result, there is uneven refraction of light, causing objects to appear to waver from side to side. In addition, the top of the hot layer of air next to the pavement reflects the sky light just as a pool of water does. These combined activities make you think you see a pool of cool water on the distant pavement ahead. As your car moves toward the "pool," this "body of water" appears to move farther away.

Objects in Water

Because of refraction, a water body always looks shallower than it really is, and an object, such as a rock, in the water will seem to be higher up than it really is. This happens because each ray of light coming from the object is refracted away from the normal as it travels from water to air to your eyes. You judge the rock to be in the direction from which the refracted ray is coming and therefore see it placed upward.

Similarly, oars and bodies in water appear pushed to one side and closer to the surface.

Total Internal Reflection Prevents Refraction

When does this happen? Suppose a light ray is trying to pass from water (optically more dense) into air (optically less dense). According

to the Laws of Refraction, this incident ray must be bent away from the normal when it emerges as a refracted ray in air. Consider other incident rays trying to pass from water to air. Those that strike the surface at greater angles of incidence will be refracted more. Finally, an incident ray will strike the surface at such an angle that it will emerge along the surface between the two media. The angle of refraction

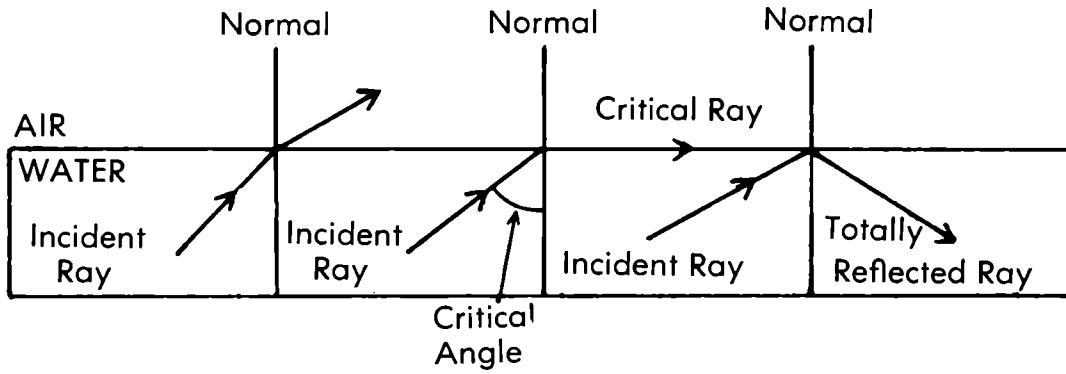


FIG. 19 *Total internal reflection.*

in this case will be 90°. The incident angle that caused this to happen is called the *critical angle* of that substance, in this case, water. Any ray coming through the water that hits the surface at an angle greater than the critical angle cannot be refracted. It is totally reflected back into the water.

Total internal reflection is very useful in optical instruments. The total reflection prism is one example. Its sides meet at right angles. Light rays that go straight into this prism hit the back surface and are totally reflected within the glass prism. Therefore, the clear back surface of the prism acts as a perfect mirror—a better reflector than a silvered mirror and more permanent, too. Large periscopes and prism binoculars use these prisms to produce erect images.

Fiber optics uses the total internal reflection of light in solid rods made of glass or plastic to "pipe" light to any place where it is needed. When light rays enter one end of a solid rod of glass or plastic, whether narrow or wide, they cannot get out. They are totally reflected within the rod, whether straight, curved, or twisted, until they reach the other end. Now bundles of thousands of threadlike glass fibers are used to transmit images where needed—even around corners. If an image is

formed at one end of the bundle, each fiber will pick up light from a tiny section of the image and internally reflect it again and again until it reaches the other end. Each fiber does its part, but to get a complete image of an entire picture, all fibers of the bundle must lie in parallel formation. These fine fiber bundles are used for internal medical examinations and in communications . . . more later.

Controlling Refraction: Lenses

Refraction can be controlled for our own needs by the use of lenses. Of course, there is the lens in each of our eyes, and there are lenses made of glass shaped and ground to refract light as much or as little as we desire.

Definition of a Lens

A lens is a piece of glass or other transparent substance whose sides are very smooth spherical surfaces. Each surface of a lens is part of a sphere. The line joining the centers of these spheres is called the principal axis of the lens.

Kinds of Lenses

There are two general types of lenses: a converging or convex lens, thickest in the middle and getting gradually thinner toward the edges; and a diverging or concave lens, thinnest in the middle and getting gradually thicker toward the edges.

In a converging lens, parallel rays are brought to a focus. The thicker the converging lens, the sooner the rays are brought to a focus, because the focal length is shorter.

A real image of an object is formed.

We follow only 2 light rays from point A. One passes through the center of the principal axis of the lens. The other is refracted by the lens and passes through the focal point (point F). This ray is extended to meet the other ray at A′. Both rays converge at A′. Every point of the candle has its image formed this way. So there forms a real inverted image of the candle (or any object you choose), smaller than the candle itself. When the convex lens is placed less than 1 focal length from the object, an enlarged virtual erect image is formed. The lens is then

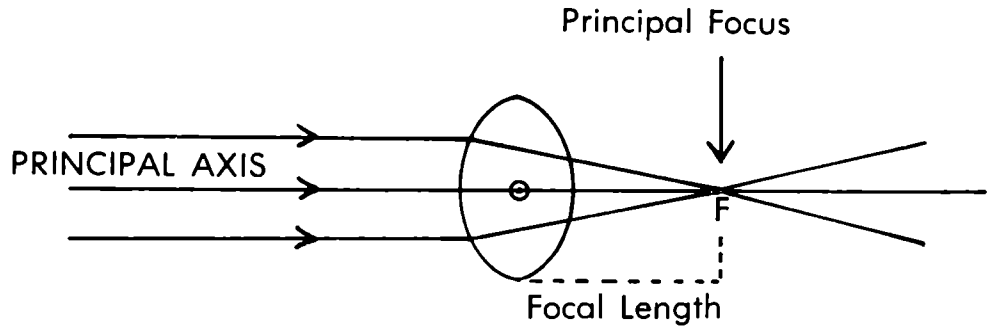


FIG. 20 *How a converging lens works.*

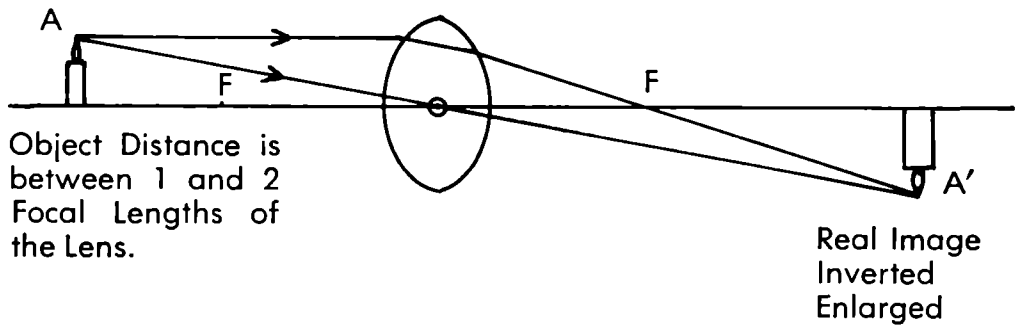


FIG. 21 *Image formation with a converging lens.*

a magnifying glass and the image produced can be seen only when looking through the lens.

In a diverging lens, parallel rays do not meet. If we extend the diverging rays by drawing a line back through the lens, the extended lines meet at a point F′, called the virtual principal focus. Light rays never pass through it.

Diverging lenses form only reduced virtual images.

Uses of Lenses

Converging lenses—convex are used:

- to concentrate light—searchlights, spotlights
- to record the real image of an object on film—cameras
- to project the real image of an object on a screen—projector
- to project the real image of an object on the retina—human eye
- to correct farsighted vision—eyeglasses
- to enhance vision—microscopes, telescopes (terrestrial and refracting—astronomy)
- to produce enlarged virtual images—magnifying glasses

Diverging lenses—concave are used:

- to correct nearsighted vision—eyeglasses
- to enhance vision (in conjunction with converging lenses—field and opera glasses

SUMMARY

Diffraction

Diffraction is the slight bending of light around the edges of an object in its path.

Diffraction supports the wave theory of light.

A diffraction grating is an instrument using thousands of transparent slits to spread light out into its various wavelengths. Diffraction patterns are formed that can be photographed.

Diffraction gratings are used to measure wavelengths of light.

Crystals are natural diffraction gratings. They are used to help measure the wavelength of X-rays.

X-ray diffraction is used to study crystal structure and molecular structure.

The resolving power of a lens is its ability to overcome the diffraction effects of two very close points. Said another way, the resolving power of an optical instrument is the ability of its lenses or mirrors to produce clearly distinguishable images of two objects that are very close together.

Refraction

Refraction is the bending of a light ray as it passes at an angle (obliquely) from one transparent medium to another.

Laws of Refraction

1. A light ray entering a second medium at right angles is not refracted.
2. A light ray passing obliquely from one medium of lower optical density to another of higher optical density is refracted toward the normal (air to water).
3. A light ray passing obliquely from one medium of higher optical density to another of lower optical density is refracted away from the normal (water to air).

The index of refraction of a substance is the ratio of the speed of light in air or in a vacuum to its speed in that substance.

Total internal reflection occurs when an incident ray approaches the surface between an optically more dense and an optically less dense medium at such an angle that the angle of refraction would be more than 90 degrees. The light ray is then totally reflected internally. It cannot escape.

Lenses

Lens	*Image*	*Image Position*	*Size of Image*	*Uses*
Converging (Convex)	Real	Inverted	Larger or smaller than the object, depending on distance of object from lens	Microscopes Telescopes Eyeglasses to correct far-sightedness
	Virtual	Erect	Larger than object if object is less than 1 focal length from lens	Magnifying glass
Diverging (Concave)	Virtual	Erect	Smaller than object	Field glasses Opera glasses (with convex lens) Eyeglasses to correct near-sightedness

Uses of Refraction

1. Detect synthetic (fake) diamonds.
2. Detect food substitutes.
3. Prisms with total internal reflection in fiber optics, binoculars.
4. Lenses in optical instruments.

IV

Prisms and Rainbows

People have always been curious about the colors they saw around them: the colors of flowers, berries, minerals, people, the earth, and, of course, the occasional rainbow in the sky. They studied objects far and near in an attempt to discover the secrets of color. To bring distant objects and tiny objects into view, they began to use lenses. The telescope and microscope were invented. Many improvements were made in these instruments over the years, but in 1600, when telescopes were first actively used in Europe, there developed a pressing need to increase the magnifying power of the lenses involved. So the lenses were made very thick in the middle to shorten their focal length. As the lenses became more convex, however, the images seen by the observers increasingly showed fringes of color on their edges, making it impossible to observe a clear, accurate image. We now know how to correct this defect, but at that time scientists and Cambridge University student Isaac Newton did not. Relying on his hobby of lens grinding, Newton tried grinding lenses in different ways to obtain better images in the telescope he built. Try as he would, he could not get rid of those fringes of color. The problem continued to haunt him. He decided to try some experiments and hit upon the idea of using a prism.

What is a prism? The dictionary defines a number of kinds of prisms that exist today:

> "An optical appliance consisting of a transparent medium so arranged that the surfaces which receive light form an angle with each other; usually of a triangular form with well-polished sides, and composed of glass, quartz, a liquid cell with glass sides, or of some other transparent reflecting substance."

"Achromatic prism—a prism transmitting light highly refracted but not dispersed. To do this a prism of flint glass is superimposed on one of crown glass having a different refractive index."

"Nicol's prism—a polarizer . . ."

Isaac Newton used a triangular glass prism. It is really like one half of a convex lens.

Newton, the Triangular Prism, and White Light

In his room in Cambridge University, twenty-three-year-old Newton pulled down the window shades. In one shade he made a small hole. Through this hole, a narrow beam of sunlight streamed into his room. Newton held the triangular glass prism in the path of the beam. To his amazement and delight, a bright patch of color appeared on the opposite wall containing all the colors of the rainbow in this order: red, orange, yellow, green, blue, indigo, and violet! Each color blended smoothly into the next. To this band of colors that had appeared, Newton gave the name *Spectrum,* the Latin word for "appearance."

Could it be that the prism could change sunlight (white light) into all those colors? Or were all those colors in the sunlight to begin with, not showing up until they were spread out by refraction in the prism? Newton thought the second situation was probably correct. After all, had he not seen the rays bending toward the base of the prism? To test his hypothesis (idea), he put another prism behind the first one but inverted the second prism. Immediately, the spectrum on the wall changed back to a spot of ordinary sunlight (white light). All those

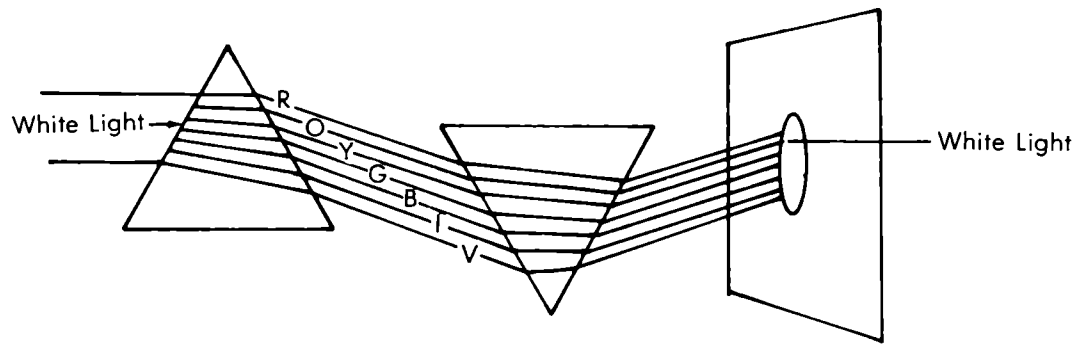


FIG. 22 *The spectrum of white light—Newton's experiment.*

spectral colors that were spread out by the first prism were brought together by the second one.

Then Newton had a further thought. Perhaps the spectral colors were present in the white light all the time, but as each passed through the prism, it was bent differently, with red light bending least and violet bending most. To test this hypothesis, Newton set up his most important experiment. He made a hole in each of two boards. The first board was placed near the window shade and the other about 3 meters (over 3 yards) behind the first one. One prism was placed in front of the second board and another prism behind the second board in such a way that when sunlight entered and passed through the first prism, only red light could pass through the hole in the second board. Newton marked the spot on the wall where red light hit. Leaving the second prism in place, he moved the first prism so that only violet light could enter the hole in the second board. He marked the spot on the wall where violet light hit. If Newton's hypothesis were correct, the second prism should have bent the violet light more than the red, so that the violet spot would appear lower down on the wall than the red spot. That is exactly what did happen!

From these and other experiments, Newton concluded that:

1. White light is not a single color. It is a mixture of many colors of light.
2. A prism does not create colors. It separates out the colors that are already in white light.
3. As white light passes through a prism, each color is refracted a slightly different amount. Red light is refracted least. Then in increasing order come orange, yellow, green, blue, indigo, and violet. Violet light is refracted least.

When these colors of light are mixed together again, the eye sees only white light.

Dispersion and White Light

White light is refracted when it enters a triangular glass prism (going from air into the optically more dense glass) and again when it leaves the prism (going from glass to the optically less dense air). Out of the prism comes a band of colors that can be caught on a screen.

This separation of white light into the colors of which it is composed is called *dispersion,* and the resulting array of colors is called its *spectrum.* Sunlight is not the only source of white light. Ordinary electric light bulbs produce white light when their tungsten filament is heated. Light given off by fluorescent lamps, candles, or any other source of light can be dispersed when passed through a triangular glass prism. Each source of light will then form its own characteristic spectrum.

Speed, Wavelength, Frequency, and Color

The complete explanation of color was not discovered until after Newton's time. Scientists discovered that color is related to the length of its waves. The measurement of waves proved that each color in the visible spectrum consists of waves of a specific length. These waves are so short that they are measured in millionths of an inch. The shortest (violet) measures about 15 millionths of an inch, and the longest (red) measures nearly 30 millionths of an inch. Scientists use the metric system and measure wavelengths of light in Angstrom units, abbreviated Å. Wavelengths of light range from 4000 A to 7500 A.

As white light enters a triangular glass prism, all the colors of light are slowed down because of the greater optical density of glass. Red light is slowed down the least and therefore is refracted least. Violet light is slowed up most and therefore is refracted most. The colors in between are refracted by amounts that increase gradually from orange to indigo because the speed of each light through the prism is correspondingly increased. Notice that red light has the longest wavelength, and violet, the shortest. The longer the wavelength, the less the light is refracted by the prism. The shorter the wavelength of a color of light, the more it is refracted by the prism. The frequency of a color of light does not change when it passes from one medium to another. We can express these relationships by the following word equation:

SPEED	= FREQUENCY X WAVELENGTH
(Red) Speed greatest Slowdown least Refraction least	Frequency X Longest Wavelength
(Violet) Speed least Slowdown greatest Refraction most	Frequency X Shortest Wavelength

To clarify, the measure of a wave is called its wavelength. The diagram represents waves. The distance from crest to crest is one wavelength and the distance from trough to trough is one wavelength.

We now know the wavelength of each color of light.

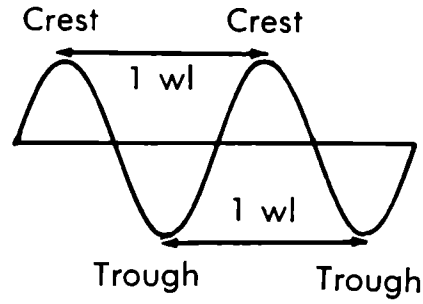


FIG. 23 *One wavelength.*

The number of crests that pass a given point in a given time is the *frequency* of the wave. The longer the wavelength, the lower its frequency and energy (fewer can pass the same point in a given time). The shorter the wavelength, the higher its frequency and energy (more can pass the same point in a given time).

The Prism Spectroscope

This is a scientific detective that uses a triangular glass prism as its main part. It separates and analyzes light coming from any source far more precisely than can any triangular glass prism alone. On one

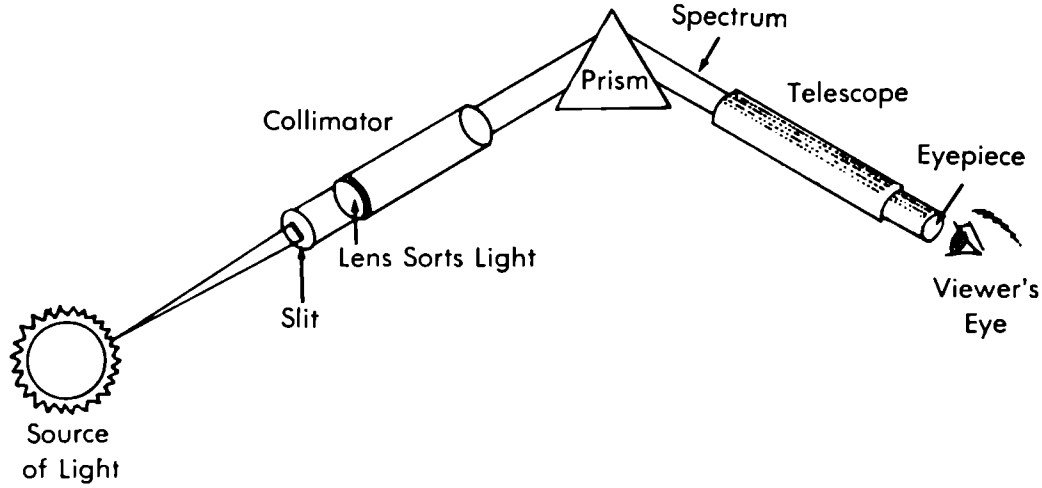


FIG. 24 *The prism spectroscope.*

side is a tube called a collimator, which has a slit at one end and a lens at the other. Light to be analyzed is passed into the spectroscope through the slit. A beam of parallel rays sorted out by the lens is sent to the prism to be refracted and dispersed. A spectrum is formed. The observer views the spectrum through the telescope at the opposite end of the spectroscope. A scale built into the spectroscope enables the scientist to measure the wavelengths of the colors he observes.

About one hundred years ago experimenters proved that each kind of material put separately into a flame and viewed through a spectroscope shows its own special pattern of lines in its spectrum. Therefore, the prism spectroscope is used to identify substances and to detect the presence and quantity of substances present in amounts too small to be analyzed chemically. In crime laboratories, it is used to help detect traces of poison in the body of a murdered person, to identify gun-bullet relationships, and to identify car-victim relationships through study of paint particles.

The prism spectroscope is also an excellent detective for astronomers. One interesting job involved the discovery of helium. Astronomers could not interpret one pattern of lines in the sun's spectrum that seemed to them not to match any chemical element then known on earth. Several years later, however, a "new" gas was discovered in the earth. It was studied using the spectroscope. Lo and behold! The lines of its spectrum matched the strange lines in the sun's spectrum. So the scientists decided to name the new gas "helium" after the Greek word *helios,* meaning sun. Helium is found in the sun, and on earth in our atmosphere, in uranium ore, and in natural gas. Astronomers can study stars with their hot, luminous gases billions of miles or thousands of light years away. Using the spectroscope, they analyze the chemicals found in these heavenly bodies by studying their spectra. From these studies, they have found that everywhere in the universe the same elements are found. Amazingly, atronomers can also learn from spectroscopic analysis how fast and in what direction a star or other light source is moving. We will find out how later in the chapter.

Types of Spectra, Their Characteristics and Uses

The *continuous spectrum* is obtained from a very hot, glowing solid or liquid, or a glowing gas under high pressure. There are no big gaps

from red to violet. Some colors may be brighter than others if the source is hotter. When a scientist locates the brightest part in the spectrum, he can tell how hot the source is. The sun's spectrum is brightest in the yellow range and has been estimated to have a temperature of 10,000° F in its outer layers. Some blue-white stars have a temperature of 100,000° F or more.

The *bright line spectrum* is produced by the atoms of glowing gases under low or normal pressure, when stimulated by heat or an electric discharge. This spectrum is made up of individual lines of color separated by dark spaces. Each element produces a characteristic bright line spectrum unlike that of any other element. It is the "fingerprint" of the atoms of that element. This spectrum, together with the wavelength of the color of light lines showing up, is used to identify positively very small quantities of an element.

The *dark line* or *absorption spectrum.* To Newton, the sun's spectrum appeared continuous. By 1802 better instruments showed that the sun's spectrum had many dark lines along its path. A Bavarian optician, Joseph Fraunhofer, observed and mapped thousands of these dark lines, now named Fraunhofer lines. They tell us that the sun's atmosphere of relatively cooler gases is absorbing some of the wavelengths of light coming from the main part of the sun. Which wavelengths? The same wavelengths of light these elements give off naturally in their own spectra. Elements in the gaseous state absorb the same wavelengths of light that they emit naturally. For example, the bright line spectrum of sodium always shows two yellow lines in a particular location. Suppose we use a spectroscope to examine the sun's spectrum. We find two dark lines in the same location as the yellow lines are in the bright line spectrum of sodium. This tells us that the sun's atmosphere is absorbing sodium and that sodium vapor (gas) is present in the sun's atmosphere. In this way scientists learned of other chemical elements present in the sun's atmosphere by absorption. That is why the dark line spectrum is also called the absorption spectrum.

The *electromagnetic spectrum.* As mentioned earlier, James Clerk Maxwell's work in the later 1800's showed that light is an electromagnetic wave. Visible light is just a small portion of the electromagnetic spectrum. The entire electromagnetic spectrum includes in decreasing order of wavelength: radio waves, infrared, visible light, ultraviolet, X-rays, gamma rays, and cosmic rays. We shall consider invisible light in the next chapter.

The Doppler Effect

The Doppler Effect is the change in frequency of the waves received by an observer whenever the wave source and the observer are moving toward or away from each other. It applies to all kinds of waves: sound, light, etc. For example, as a sound comes closer to you, more sound waves per second enter your ear and you hear a higher and higher pitch. If light waves change in frequency relative to the source and you, you notice a change in the color of light. If the distance between the light source and you is decreasing, the frequency of the waves becomes greater than that of the source, the wavelength is decreased, and the light appears more violet than it would if it were not moving toward you. If the distance between the light source and you is increasing, the frequency is decreasing, the wavelength increasing, and the light appears more red than it would if it were not moving away from you.

With reference to light, the Doppler Effect, also called the Doppler shift, is useful to the astronomer. He analyzes light from the sun, stars, and other heavenly bodies. He then compares the spectrum of each of many elements on earth with the corresponding spectrum from a star and observes whether the shift is toward the blue or red end of the spectrum. If toward the blue, the star is approaching the earth. If toward the red, the star is moving away from us. The spectrum from each of many stars has been found to have color shifts toward the red end. The same is true of nebulae. The shift of the spectra of so many heavenly bodies to the red end has been interpreted to mean that, in general, they are moving farther and farther away from us, other galaxies are racing away from us, and the universe itself is expanding.

The Doppler Effect is applied in the operation of radar. Radar is used to measure the velocity of approach of airplanes, cars, storms, etc. The transmitter at the radar base sends out an electromagnetic wave on a narrow beam that hits metallic objects. The wave is reflected by the metal or other surface. It is picked up by a radar receiver. If the object is not moving, the reflected wave has the same frequency as the wave sent out by the transmitter. If the object's distance is increasing, the reflected frequency is less than the transmitted radar frequency. If the distance is decreasing, the reflected frequency becomes

greater. The greater the velocity of the object, the greater will be the change in frequency. That is how speeders on the highway are caught.

Rainbows—Prisms in the Sky

"A rainbow! A rainbow in the waterfall!" gleefully exclaimed Joan. "Please let me go down closer. I want to see if I can touch it." Thus pleaded the little girl as she sat finishing lunch with her family in a hotel restaurant tucked high up on the mountainside. Their table faced a huge picture window through which a thundering cascade of water could be seen tumbling into the gorge below. The sun shone brightly on the waterfall and the rainbow could be seen in the mist of the back spray below. A descending wooden walkway had been provided for guests wishing to explore "down below." In a holiday mood, the family agreed. As they moved carefully down the walkway, Joan looked in the direction from which she thought the rainbow had come.

"Where is it? I don't see it." The family continued down. But nowhere was the rainbow to be seen. Why?

To discover why, let us first find out how rainbows are formed in the sky.

Rainbows are usually seen at the end of a rainstorm when clouds have cleared and bright sunlight shines through, striking drops of water suspended in the atmosphere. When sunlight strikes a single raindrop, some of it is reflected from the outer surface, some of it passes right through, and the remainder strikes the drop obliquely. That part is refracted as it passes from air into water. The white light is dispersed. The spectral colors strike the inside back surface of the drop and are reflected back so that the raindrop emits the familiar spectrum of dispersed white light—red, orange, yellow, green, blue, indigo, violet. The raindrop has dispersed the sunlight just as a prism would. But we have considered only one raindrop. To see a rainbow, you must be standing between the sun and the raindrops. The colored lights coming from the drops must strike your eyes at a particular angle. This is possible only when the colored lights come from raindrops that form an arc (part of a circle) in the sky.

You can see, then, that a rainbow is the result of sunlight entering raindrops at a "proper" oblique angle, being refracted by them and

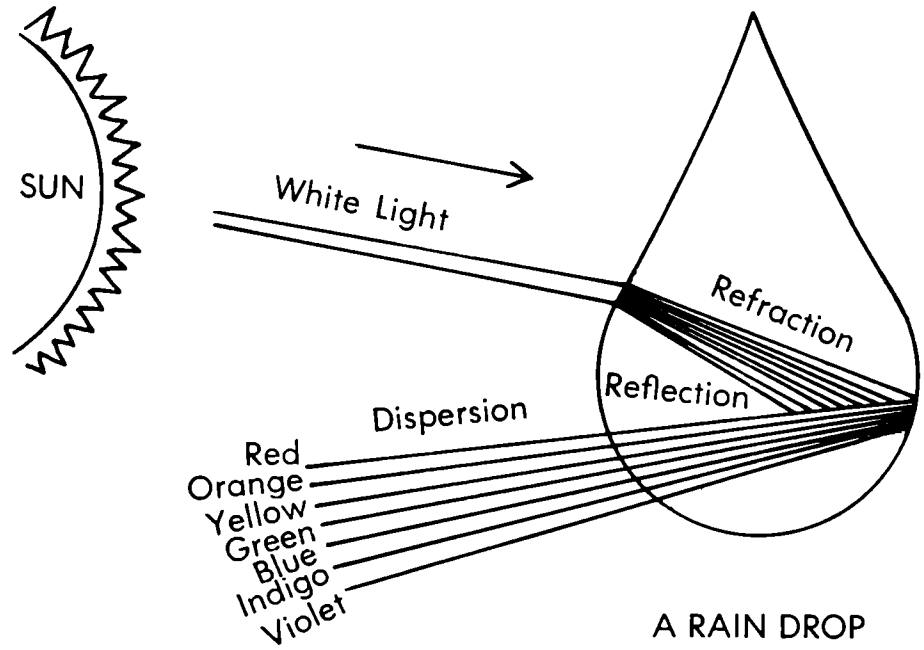


FIG. 25 *Light and a single raindrop.*

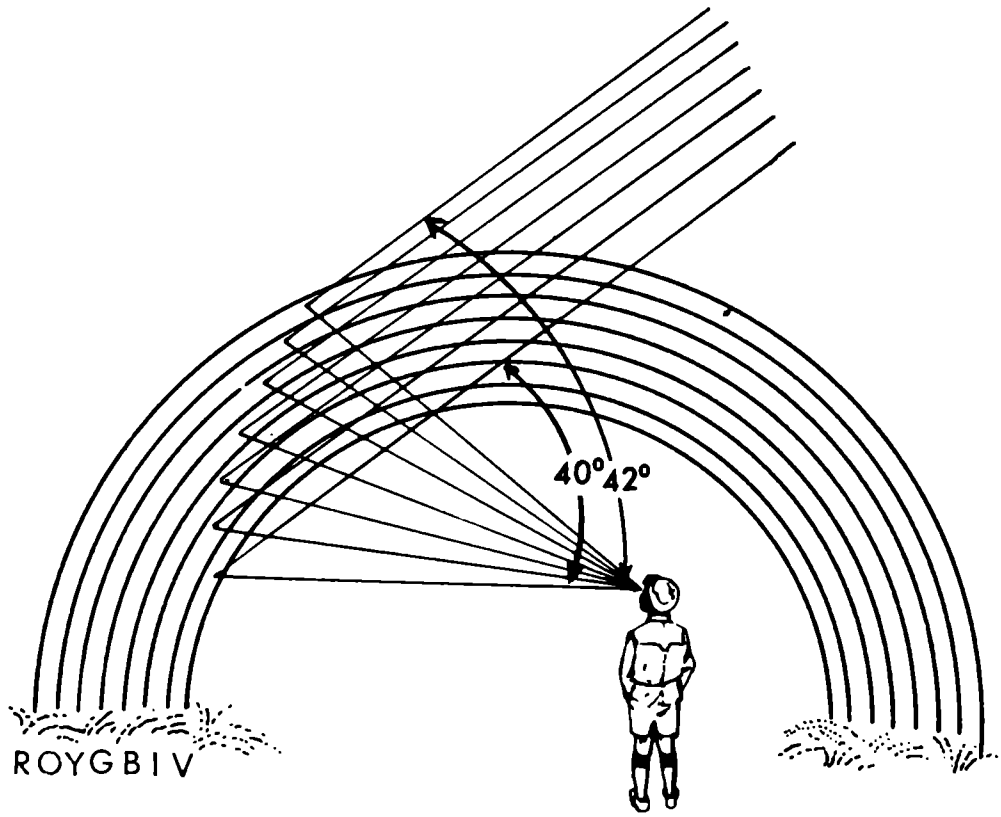


FIG. 26 *A rainbow after the rain.*

reflected back to your eyes at a "proper" angle. When these conditions are met, and the atmosphere is clear, you will see prisms in the sky, called a rainbow.

Why couldn't Joan see the rainbow in the waterfall once she left her seat? Of course, the angular relationships had changed so that the colors of the rainbow could not be reflected back into her eyes.

Pollution is a rainbow killer. Particles of soot, ash, and dust absorb some of the sunlight that strikes them but scatter most of it from particle to particle. Light does enter raindrops, but scattering prevents it from entering at the "proper" angle in most cases. Not enough light to produce a rainbow can enter the raindrops. Even if, by chance, colored light is formed, the particles in the air will scatter the light so that it will never reach your eyes at the "proper" angle for sight. Pollution does kill rainbows in two ways. Work to reduce pollution.

SUMMARY

Triangular Glass Prisms

A prism is an optical instrument made of carefully polished clear glass so shaped that the surfaces that receive light form an angle with each other, making a triangle.

Newton, the Triangular Prism, and White Light

1. Newton discovered that when white light enters a triangular prism at an angle, it is spread out into a series of colors: red, orange, yellow, green, blue, indigo, violet.
2. The spreading out of white light is called dispersion.
3. The array of colors is called a spectrum.
4. As white light enters a prism, each color is bent (refracted) a slightly different amount: red light the least and violet light the most.
5. Refraction causes the dispersion of light.
6. When colors of the sun's spectrum are mixed together again, the eye sees only white light.
7. Sources of light other than sunlight can be dispersed. Each will form its own characteristic spectrum.

Speed, Wavelength, Frequency, and Color

1. The color of light depends upon its wavelength.
2. The longer the wavelength, the less it is slowed down when it enters a prism and the less it is refracted.
3. The longer the wavelength, the lower its frequency and energy.
4. Example: Red light has the longest wavelength, is slowed down least on entry into a prism, is refracted least, and has the lowest frequency and energy when compared with the other colors of the spectrum. The reverse is true of violet light, with the shortest wavelength.

The Prism Spectroscope

1. It separates and analyzes precisely light coming from any source.
2. It is used in detective work to identify traces of materials.
3. It is used in astronomy to identify elements in heavenly bodies by studying spectra and comparing them with the spectra of elements on earth.
4. It is used to determine the speed and direction of movement of heavenly bodies relative to the earth.

Types of Spectra

Continuous Spectrum—From very hot, glowing solid, liquid, or gas under high pressure. Example: the sun's spectrum.

Bright Line Spectrum—From atoms of glowing gases under low or normal pressure, when stimulated by heat or electric discharge. Individual lines of color separated by dark spaces. Example: each element produces a characteristic spectrum.

Dark Line or Absorption Spectrum—Fraunhofer lines take the same position as the characteristic bright line or lines of an element, but these dark lines are in the sun's spectrum. They identify an element absorbed by the sun's atmosphere.

Electromagnetic Spectrum—In descending order of wavelength, it consists of radio waves, infrared, visible light, ultraviolet, X-rays, gamma rays, and cosmic rays.

The Doppler Effect

If light is moving toward you, the distance between the light source and you is decreasing, the frequency of waves increases, the wavelength decreases, and light appears more violet.

If light is moving away from you, the distance between the light source and you is increasing, the frequency of waves decreases, the wavelength increases, and light appears more red.

Red shift tells us that the universe is expanding.

Radar uses the Doppler Effect to determine speed and direction of moving objects.

Rainbows

Raindrops act as prisms. They refract sunlight. To see a rainbow, you must be located between the sun and raindrops forming an arc in the sky. When sunlight enters the raindrops at the "proper" angle, when it is refracted by the raindrops and then reflected back to your eyes at the "proper" angle, you will see a rainbow.

Pollution destroys the chance of our seeing a rainbow. Work to reduce pollution.

V

Invisible Light

William Herschel's Discovery

In 1800, about the time the wavelength of light was being determined, a German-British astronomer named William Herschel decided to investigate the temperature of each of the colors of light in the spectrum of sunlight emerging from a triangular glass prism. Starting with violet, he held a thermometer in each of the colors of light. As he moved the thermometer from violet to each of the others and finally to red, he noticed that the temperature reading rose steadily. Red registered the highest. He then moved the thermometer just beyond the red area where no light could be seen. To his amazement, the temperature continued to climb.

"There must be rays beyond the visible spectrum that cannot be seen," he thought. With further work, he discovered those rays. He called them "infrared," meaning "below the red." They were always just beyond the visible red light. They proved to be the invisible continuation of the visible spectrum.

In 1852 George Gabriel Stokes discovered invisible rays at the violet end of the spectrum. They were named "ultraviolet," meaning "beyond the violet."

Since then, scientific knowledge has added many other invisible rays to both ends of the visible spectrum. In 1867 James Clerk Maxwell proposed the electromagnetic theory of light. Today, that theory includes all waves, visible and invisible, that travel through space. So we have an electromagnetic spectrum or family of waves, visible and invisible, varying in the way each interacts with matter, but united

by the one characteristic they have in common: they all travel at the same speed, 186,000 miles per second (or 300 million meters per second), the speed of light in a vacuum. These waves vary widely in wavelength, from gamma rays with wavelengths shorter than a billionth of an inch, to radio waves with wavelengths up to about ten miles. Their radiant energy enables them to travel through space.

Parts of the Electromagnetic Spectrum

Let us discuss the properties and uses of each kind of ray found in the electromagnetic spectrum.

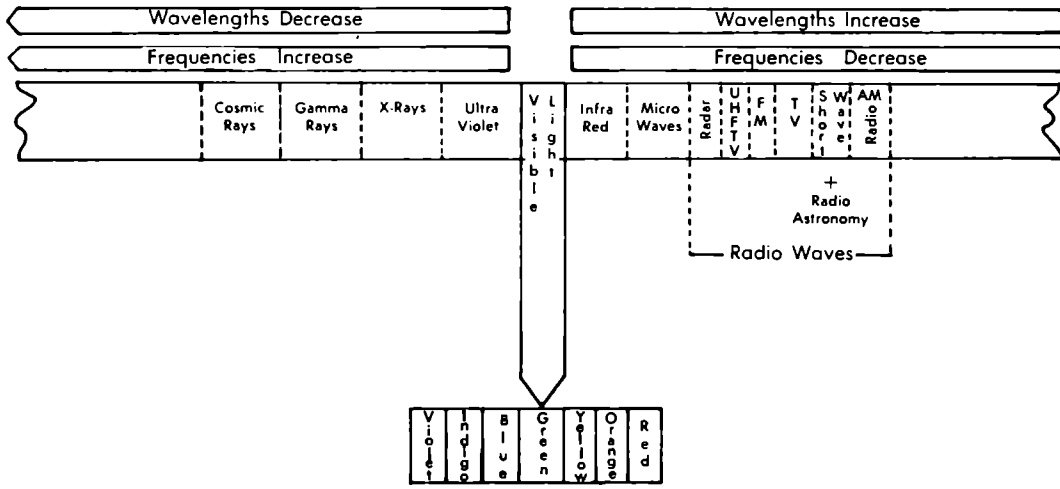


FIG. 27 *Chart of the electromagnetic spectrum.*

Infrared Rays

Infrared rays are also called heat rays. They are invisible. Their wavelength is a bit longer than that of red rays, their frequency is less. They are the means by which heat is radiated (sent out) through space. If you sit in the sun or near a warming device, your body absorbs these rays. Their energy increases the speed of motion of your own molecules, and your temperature rises. You feel warm. Fortunately, if you are in good health, your body will quickly reduce this temperature by making you perspire. Perspiration evaporates, and you feel cooler. Your body then radiates some of the absorbed infrared rays. All substances not at absolute zero (the lowest possible temperature) radiate

infrared rays. The heat you experience from a glowing electric light bulb, an electric iron, a radiator, a hot pavement, a group of people in a crowded room, is all caused by the radiation of infrared rays from these bodies.

Special infrared lamps are used when high, steady heat is needed. Paint on new cars is dried this way. Food in some large restaurants can be kept warm this way.

Sensitive instruments have been devised to measure infrared radiation. Some are used by astronomers to measure the temperature of stars. Others are placed in guided missiles where they can detect, if necessary, infrared rays coming from the motor of an enemy plane. This radiation then sets the controls of the missile to fly off directly to meet the intruder.

Camera film sensitive to infrared waves is used to take clear pictures at a distance or nearby, on land, at sea, or from the air, through light or darkness, mist or haze.

Ultraviolet Rays

Ultraviolet rays are invisible. They have shorter wavelengths than do violet rays, and their frequency is higher. Ultraviolet rays cannot pass through ordinary glass. Therefore, ultraviolet lamps are made of transparent quartz, a mineral that lets these rays pass through.

Ultraviolet lamps are used to kill germs in hospitals. Some people use them to "get a good tan." WARNING: Too much time spent under UV lamps can result in serious skin burns. Ultraviolet light does not make us feel uncomfortably warm because it does not warm the skin surface as infrared would. The burn damage is done before you know it.

In the open air, ultraviolet rays are present even on a cool, cloudy day. You can be badly "sunburned" by these rays before you know it. Fortunately, the ozone layer in the upper atmosphere filters out most of these rays coming from the sun. Otherwise, living things on earth would be killed. The astronauts and their spacecraft in flight lost the protection of our atmosphere. For that reason, their outfits and spacecraft were equipped with good ultraviolet filters. Recently, it has become obvious that continuous exposure to ultraviolet rays often results in skin cancer. Sun screen lotions, applied before going outdoors,

filter out most but not all of the harmful ultraviolet rays. They do allow the beneficial rays to pass through to us.

In spite of all the dangers of overexposure to UV rays, you must get some sunlight. The UV rays are needed to change some chemicals in our body into vitamin D, which helps build strong bones and teeth and prevents rickets. Milk and other foods are irradiated by UV lamps in order to produce some vitamin D.

These invisible rays are also important in photography. They cause chemical changes in photographic film enabling us to take pictures and have them developed.

Certain minerals, oils, plant juices, and chemicals glow when exposed to UV light. If they glow only as long as the UV light strikes them, they are *fluorescent materials* and the activity is called *fluorescence.* If the substances continue to glow after UV radiation has been removed, they are *phosphorescent* and the activity is called *phosphorescence.* At home, your fluorescent lamp is a tube filled with mercury vapor. When electricity flows through the mercury vapor, invisible ultraviolet light is produced. It strikes the inside surface of the tube, which is coated with a mixture of chemicals called phosphors. They fluoresce; that is, they give off visible light when excited by ultraviolet radiation. The color a fluorescent lamp produces depends on the particular phosphor inside. Perhaps you have a watch or clock whose numbers glow in the dark. Phosphorescent material, painted on the numbers, absorbs UV light by day and glows blue-green by night. In the theater, costumes and stage props may be painted with various fluorescent compounds. In the darkness of the theater, an invisible beam of ultraviolet light is played upon the stage. Suddenly, glowing multicolored figures begin to dance. The scene comes into view—all in black light, the name often given to ultraviolet light.

Again, there is detective work to be done. Special UV lamps enable police to identify blood stains amid paint spots. Each fluoresces differently. Forged documents and secret messages can be identified by the different colors they reveal when UV light shines invisibly on the slightly different kinds of dry ink. To some extent, frauds in art work and antiques can also be detected by experts using this technique.

X-Rays, Gamma Rays, and Cosmic Rays

On the ultraviolet side of the electromagnetic spectrum are X-rays,

gamma rays, and cosmic rays with progressively shorter wavelengths, higher frequencies, and greater energy content.

X-Rays

In 1895 Professor Wilhelm Roentgen was experimenting with a special kind of electric bulb called a cathode ray tube. It was covered completely with black paper. As he had done so often before, he turned the light on. Unexpectedly, this time a piece of paper at the other end of his workbench glowed brightly. It had been treated with a fluorescent compound in preparation for a different experiment. He turned off the current. The glow disappeared.

"Why the glow?" thought Roentgen. Perhaps something invisible to him was coming from the covered bulb and striking the distant paper. He did not know. So he called the unknown, X-rays. He soon discovered that these rays could penetrate two decks of cards, a thick block of wood, a thick book, and, to his surprise, the flesh of his hand but not the bones. He could see shadows of his hand bones on a fluorescent screen when the bulb was turned on and his hand was held between it and the screen. He soon discovered that these shadows could be captured on a photographic plate (film). He made the first X-ray photograph. Doctors began to use X-rays to help them set broken bones. But Roentgen continued to study the basic nature of X-rays. He showed that X-rays, like light, travel in straight lines and can be reflected by mirrors. Twenty years later, scientists were able to prove X-rays to be electromagnetic waves with very short wavelengths, very high frequencies, and much energy. They are produced when electrons travel at great speeds in a near vacuum and are suddenly stopped.

Later the X-ray machine was developed. It gave off X-rays that could affect a photographic film. It was and is used by doctors to help set bones, to locate foreign metal objects in a person, and to study the digestive system with the aid of barium salts, which absorb X-rays. The shadow can also be observed on a fluorescent screen in the doctor's office. X-rays are also used in proper dosage to kill cancer cells.

Dentists use X-rays to locate cavities and to study the condition of the bone structure of the upper and lower jaws.

Recently the medical profession has decided to use X-rays only when absolutely necessary, because the rays have been linked with the onset

of cancer. Since continual exposure to them can also harm genes and chromosomes, X-ray technicians, doctors, and dentists wear rubber aprons impregnated with lead when they are in the X-ray room. This shields them against overexposure to X-rays.

In industry X-rays are used to find cracks in metal parts and locate foreign objects in packages.

Roentgen's work gave the world X-rays and led other scientists to the discovery of radioactivity in the 19th century and nuclear energy in the 20th.

Gamma Rays

Gamma rays are similar to X-rays but have much shorter wavelengths and far more penetrability. They can go through slabs of concrete as thick as 5 feet. As with X-rays, gamma rays, properly used, can destroy cancerous growth. However, both can also cause cells to grow wildly (cancer), and both can injure genes and chromosomes. Since gamma rays are given off by radioactive substances such as radium and by fallout and waste from atomic energy tests, it is important that radioactive materials be kept away from our food and water supply.

Like X-rays, gamma rays are used in industry to test machine parts to discover tiny flaws such as weak spots, breaks or holes, before the machine is offered for sale and use. Engineers also use these rays to test the metal of airplane parts and boilers. In each case, shadow pictures are taken and studied. Faulty metal is replaced and tested again for safety.

Cosmic Rays

Cosmic rays are powerful, deadly radiations coming to us from outer space, but exactly from where, scientists do not know. In space they are composed of the nuclei of hydrogen atoms and others. When cosmic rays approach our atmosphere, their high-energy rays bump into the nuclei of other atoms in their path. Everything involved breaks up (disintegrates), and the pieces fall to earth. It has been found that one of the results of cosmic ray collisions is the production of gamma rays. Our atmosphere shields us from cosmic rays themselves.

On the Infrared Side

On the infrared side of the electromagnetic spectrum are rays with progressively longer wavelengths, lower frequencies, and less energy content. In increasing order of wavelength, they are: microwaves and radio waves for communication by radar, in ultra high frequency (UHF) television, FM radio broadcasting, TV broadcasting, shortwave radio, radio astronomy, AM radio, and long wave radio.

James C. Maxwell had predicted that electromagnetic waves could be created in space by the movement of electric charges. He did not live to see his prediction tested. In 1887, however, Heinrich Hertz, a German physicist, did demonstrate waves coming from an electric discharge across the space between the knob ends of a wire loop in a simple circuit. He found that this could cause a jumping electric spark to be given off in a second similar circuit some distance away in his laboratory, whenever the first circuit was working. He covered the first circuit with a box and turned the current on. Sure enough, the second circuit worked as long as the first one was on, even though the two circuits were not connected. Why all the excitement? He was really broadcasting an electromagnetic wave from one circuit to another! He studied these waves, called, of course, Hertzian waves, and found that they had all the properties of light waves; however, they had much longer wavelengths. These are the radio waves of today.

In 1901 the Italian scientist Guglielmo Marconi used electromagnetic waves to send a weak signal across the ocean. That was the first message sent by wireless telegraphy. It opened the way for the development of radio and television, which use electromagnetic waves to send sounds and pictures all over the world, out into space, and back.

Microwaves

Microwaves are electromagnetic waves that have wavelengths in the centimeter range, up to 3 centimeters. Infrared rays are on the side of the shorter microwaves, and radio waves on the side of the longer ones. They were discovered in the 1930's. Their frequencies are useful in radio communication. They can be directed easily and have good resolving power. Microwaves are used:

- in radar, most importantly
- as carrier waves for telephone, telegraph, and TV transmission
- in microwave spectroscopy to increase our knowledge of the molecular and crystal structure of matter
- to develop the maser, a noiseless amplifier
- in radioastronomy, to study celestial bodies by measuring and analyzing their electromagnetic radiation. Dish-shaped receivers with large concave mirrors catch weak waves and focus them on a detector. Since these waves are not stopped by clouds, the heavens can be studied in any weather. Radiotelescopes have been used to map our galaxy, which turns out to be made of billions of stars arranged like a giant pinwheel.
- in high energy linear accelerators used to speed up protons
- in appliances such as ovens

Radar

Radar is an acronym for *ra*dio *d*etection *a*nd *r*anging. Microwaves, which can be kept in a narrow beam by a concave mirror, are sent out in short bursts. If they strike a distant object, they are reflected back to the radar station. Using the echo principle, the distance of the object from the station can be figured. Radar is used:

- to detect airplanes
- to help control air traffic at airports
- to help the control tower direct airplane landings from the ground
- to monitor the flight and obtain data from space probes, satellites, etc.
- to provide automatic guidance of unmanned space vehicles
- to map the earth's surface from high-altitude aircraft and satellites
- to track storms, especially tornados, hurricanes, and rainstorms
- to check the speed of cars on a highway or rockets and satellites in the sky using the Doppler Effect
- to be a part of instrument flying

Radio Waves

Radio waves used in regular radio broadcasting are up to ¼ mile

long. Electrical broadcasting equipment sends out electromagnetic waves from an antenna high above the ground. If your receiver is no farther than 100 miles from the broadcasting station, radio waves traveling along the surface of the earth will bring your program to you. Farther away, people depend on the ionosphere to send back down to them by reflection the waves that have traveled from the broadcasting station through space. In broadcasting, it is necessary to avoid interference between stations. Therefore, the Federal government assigns a certain frequency to each radio station. Voices, music, and other sound effects are changed to electricity and then carried by radio waves at a particular frequency.

Television programs are carried by electromagnetic waves from 1 to 18 feet long. They are too short to reach and use the reflecting layers of the ionosphere. To send TV programs across the United States, the waves must be carried by special cables or be relayed to tall towers about 30 miles apart. As each tower receives the wave at its antenna, it reinforces the wave and sends it on to the next tower. Radio and TV programs are beamed across the ocean by reflection from a satellite that orbits the earth.

We have now completed our brief discussion of invisible light, the various rays of the electromagnetic spectrum, each named according to the method by which it is produced or used. Invisible light travels with the speed of visible light and in many ways "illuminates" our world.

SUMMARY

The electromagnetic spectrum is a family of waves, visible and invisible, which travels at the speed of light and has radiant energy. It is divided into many bands according to wavelength and function. We recognize each of the invisible bands of light by the effects it produces; that is, by what it does and how it reacts with matter.

One wavelength is a measure of the distance between the crests of two consecutive waves.

The length of waves in the electromagnetic spectrum is measured by scientists in Angstrom units. One Angstrom unit, Å, equals one hundred millionth of a centimeter. The visible spectrum extends from

4000 to 7500 A approximately. Invisible light extends from the shortest gamma rays, .01 A, to the longest radio and electric waves.

The longer the wavelength, the lower the frequency and the less the radiant energy. The shorter the wavelength, the higher the frequency and the greater the radiant energy.

Bands of Invisible Light

Wave Band	*Wavelength*	*Characteristics*	*Uses*
Ultraviolet	4000 to 2000 A	Filtered by plain glass and ozone.	UV lamps Photography Fluorescence Phosphorescence Kills germs Aid to vitamin D production
X-rays	1.0 A	Pass through most opaque objects. Stopped by bone and metal.	Medicine Dentistry Industry
Gamma rays	0.01 A	Result of radioactivity	Cancer treatment Industry
Cosmic rays	0.0001 A	Come from outer space Very dangerous	None
Infrared rays	10,000 to 50,000 A	Heat rays	Photographic film Drying car paint Heating food Guided missiles Measuring the temperature of stars
Microwaves	Up to 3 cm.	——	Radar, masers Communications Spectroscopy Radioastronomy Linear accelerators Ovens

Bands of Invisible Light (continued)

Wave Band	*Wavelength*	*Characteristics*	*Uses*
Radar	Longer than microwaves	Uses the echo principle	Detect airplanes Control air traffic, direct plane landings, instrument landings Monitor space flights Track storms Check auto speeds
Radio waves	Up to ¼ mi. long	Use ionosphere for reflection	Communication
Television	1 to 18 ft. long	Uses towers and orbiting satellites for reflection	TV

VI

Interference and Polarization

The phenomena of diffraction, interference, and polarization of light can be explained if you assume that light travels as waves. We have already discussed diffraction. Now we turn to interference and polarization.

Interference

Newton observed interference but did not recognize evidence of diffraction even when the evidence was there. Therefore, he held to his corpuscular theory. He did not think that light might be a wave form, although he did admit that light rays might be made up of tiny segments.

Newton's Rings

Newton placed the convex surface of a lens in contact with a plane glass surface and pressed them firmly together as if he were holding a sandwich. There was a thin film of air between the surfaces of glass. He held them so that they reflected light from the ceiling of his room. Where the two pieces of glass were in contact, he saw a tiny dark spot. Around this central spot was a set of light and dark rings, called concentric rings. He studied them, but his observations did not lead him to change his mind about the nature of light. Today, using the wave theory, we say that when a beam of light enters the lens, part of it is reflected at the surface inside the lens and another part is reflected at the surface of the flat glass plate. Because the light waves travel different distances through the glass surfaces and the air film, they may be "out of phase" as they come together again. Crests would

not meet crests, and troughs would not meet troughs. The reflected waves would cancel out as the crest of one wave met the trough of the next wave. We would see darkness. Those waves that come together "in phase" show up as a bright reflection. If white light is used, alternate circles of color and darkness appear around the central dark spot. Newton's rings are formed by interference in the thin air film between a convex and a plane glass surface. Try this experiment yourself.

Huygens and Grimaldi

In the late 17th century Christian Huygens thought of light as a wave. He developed a principle that could be used to predict the behavior of light waves. Huygen's Principle said that every point on a moving wave front can be a source for secondary wavelets sent out in every direction. To him, light was a wave form.

Francesco Grimaldi observed, demonstrated, and explained the diffraction of light when it passed through very small openings. This could only happen if light travels in waves, he said.

The work of both these men was largely ignored because Isaac Newton, with all his accomplishments, dominated the scientific scene of the time, and he favored the corpuscular theory of light.

Thomas Young

In 1802 Thomas Young, an English physicist, archaeologist, and doctor, tested Grimaldi's hypothesis. Young thought that if light is diffracted as it passes through very narrow openings, it should form a pattern of intersecting waves on the side of the barrier containing the openings.

This is what he did. The light of a single wavelength from a small source (L) was made to illuminate a barrier that had 2 narrow slit openings, S_1 and S_2, very close to each other and equally distant from L. The light that passed through the slits fell on a screen. Young saw not 2 lines of light but a whole series of bright lines alternating with dark regions.

Since the light came from the same source and traveled by two different paths to the same place (S_1 and S_2), it was coherent light. This means a source of light that produces waves with a constant phase

relationship, in which crest meets crest and trough meets trough continually. Two waves in phase reinforce each other. This is called constructive interference. Two waves out of phase cancel each other (destructive interference).

Now imagine you are looking down on Young's setup. As Huygens

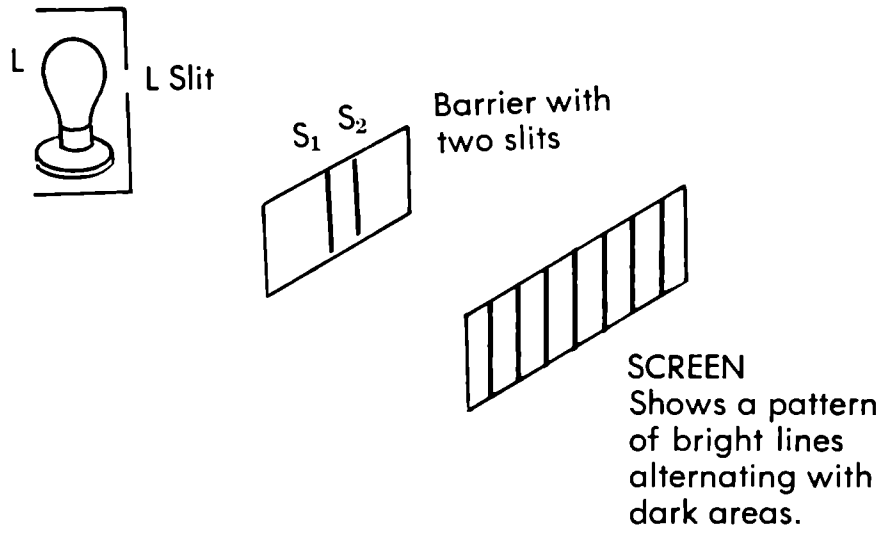


FIG. 28 *Young's experiment.*

predicted, light from the source spreads out. The wave fronts are represented by circles with L at the center. Each wave front reaches S_1 and S_2 at the same time. Parts of the wave front at each slit produce their own wave fronts (wavelets). The waves produced by S_1 and S_2 are coherent because they come from a single source, L. The secondary waves overlap on the screen and interfere with each other. Waves that arrive in phase reinforce each other and give a bright line. In between the bright lines are dark regions where the waves arrive out of phase and cancel each other.

The amazing thing is that point C, which is equidistant from S_1 and S_2, receives a central bright line. If light did not bend, how could it ever reach point C? Indeed, if light were not a wave phenomenon, if it did not diffract through the slits, the viewing screen would be completely dark. No ray traveling along a straight path could reach it from the source. But diffraction and interference illuminate the screen with this pattern of light and dark. From such patterns, it became

possible to measure wavelengths of light using an instrument of many slits called a diffraction grating.

With the work of Thomas Young and others, the wave theory of light came to be fully accepted in the 19th century.

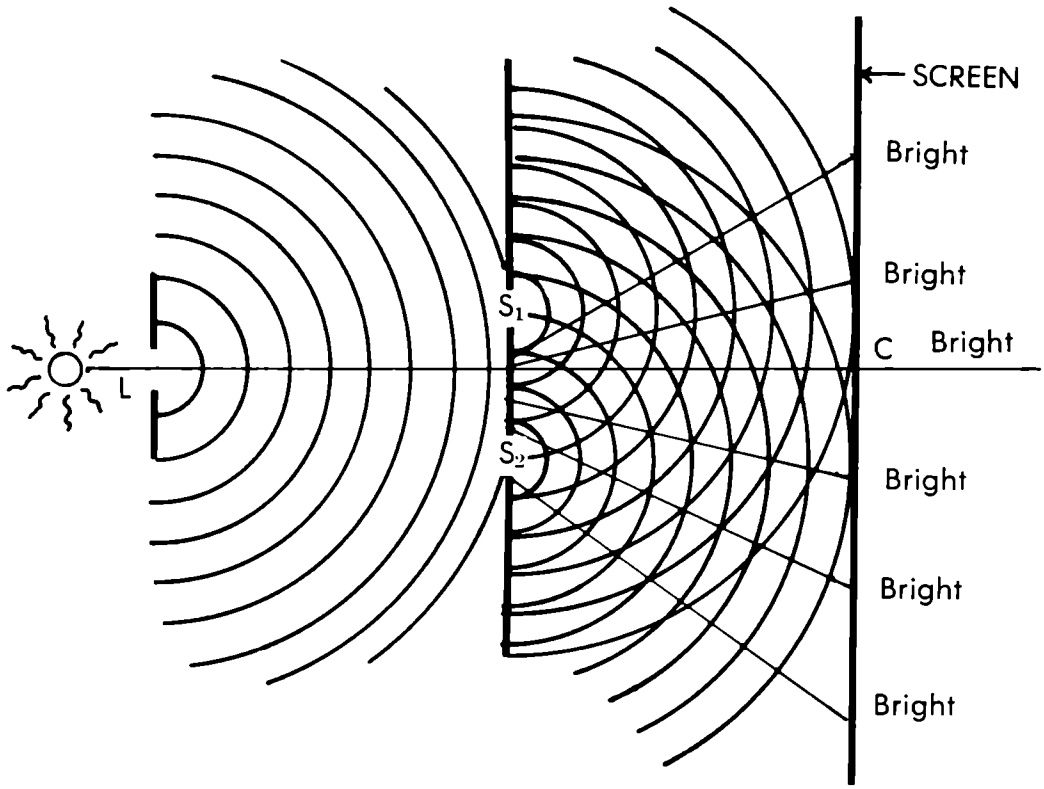


FIG. 29 *Interference pattern in Young's experiment.*

Interference With Thin Films

From early childhood you marveled at the brilliant colors produced by soap bubbles floating in air or by oil slicks lying on water in roadways. Where did the colors come from? Let us find the answer.

When you look down at a thin oil film on a wet pavement, you see light that is reflected from two surfaces—the upper and lower surface of the film. Light from the lower surface has traveled a greater distance to reach your eyes than has the light from the upper surface. Therefore, the light waves from the lower surface fall behind those from the upper surface. Suppose the thickness of this oil film causes the "fall-behind distance" to be equal to the wavelength of orange-yellow light. Then,

if orange-yellow light rays are shining on the oil at a particular time, since those rays are in phase with those coming from the oil when they meet at the surface of the oil, you will see orange-yellow light reflected at that point. Let us consider violet light. Violet rays from the upper and lower surface of the oil film are only 1.5 wavelengths apart at a particular spot. They are out of phase. They produce destructive interference at that point. No light at all will be seen there even if the light shining on the slick contains violet light. However, violet light is visible in other locations on the slick where the oil's thickness allows the distance between the violet rays coming from its lower and upper surfaces to be equal to a whole number of wavelengths. The waves will then be in phase, and violet will be reflected at that point. So it is with each color reflected at a particular spot in the oil slick. Look at the oil slick from different angles. You see different color effects because different colors of light are reflected through the different thicknesses of oil spread unevenly on the water.

The wave nature of light, the difference in wavelengths of different colors, and the interference of light waves make it possible for us to see beautiful colors in thin films of soap in solution, oil on water, and air trapped between two glass surfaces.

Uses of Interference

Interference of light is used in the *precision testing* of lenses, prisms, and mirrors for use in fine optical instruments. Their surfaces must be so flat that no spot varies by more than a few millionths of an inch. Many times during the polishing process, the unfinished glass is laid on another piece of glass known to be perfectly flat. A strong light is shone on them. Interference bands are formed by reflection from the two surfaces separated by a thin film of air. If the bands formed are straight and parallel, the glass tested is as flat as necessary. If the bands form a wavy pattern, there are imperfections in the glass that must be corrected.

A special instrument called an *interferometer* uses interference patterns to help scientists make very precise measurements of the length of an object by determining the number of wavelengths produced. An interferometer placed on the telescope in the Mt. Wilson observatory

measures the size of stars. The red star named Betelgeuse was found to be a giant star with a diameter of 240 million miles.

Prevention of Interference

Sometimes we want light waves to cancel out. For example, if all entering light rays were reflected back and forth by the surfaces of the lenses in our cameras, the images formed on the film would not be as bright and sharp as we would like. Therefore, manufacturers of fine camera lenses put a nonreflecting coating on each lens surface before assembling them for placement in the camera. The coating is just thick enough to eliminate some of the light waves by cancellation. Coated camera lenses appear purple.

Polarization of Light

Christian Huygens, the Dutch physicist, mathematician, and astronomer who lived and worked in Newton's time, was always interested in discovering more about the nature of light. One day he cut two flat slices from a crystal called Iceland spar and held them, one behind the other, in the path of a beam of light. While looking through both crystals, he slowly turned one of them. He observed that the light gradually changed from bright to dark and back again to bright. He continued to rotate the crystal. The light continued to change in the same way: bright, darker, dark, and back again slowly to bright. What is this phenomenon? How does it happen?

Scientists call this phenomenon the polarization of light. It is the process of removing from a beam of light all the vibrations except those in one direction. To understand and interpret Huygen's observations, we must first remember that:

1. Each kind of crystal has a characteristic grain running through it in one particular direction.
2. The direction of this "grain" is called the axis of the crystal.
3. A plane is a surface, real or thought of, containing all the straight lines connecting any two points on it.
4. A wave is a vibrating motion that travels along in a given direction.

5. Transverse waves are those in which the vibrations of particles or forces are perpendicular (at right angles) to the direction in which the waves are traveling.
6. Light waves are transverse waves.
7. Light waves are not made of particles. They are composed of electromagnetic forces vibrating in all possible directions perpendicular to the direction in which the waves are traveling. Huygens did not know about this, but we do. In the 1860's James C. Maxwell developed the electromagnetic theory of light.

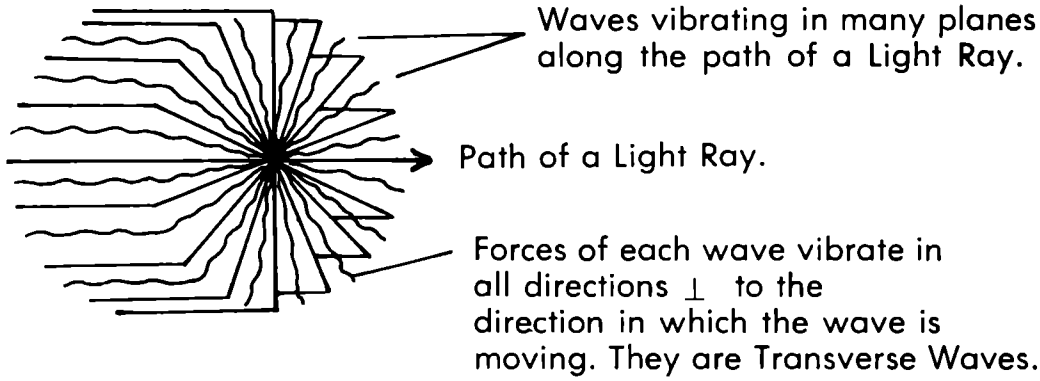

Waves vibrating in many planes along the path of a Light Ray.
Path of a Light Ray.
Forces of each wave vibrate in all directions ⊥ to the direction in which the wave is moving. They are Transverse Waves.

FIG. 30 *A transverse wave.*

Explanation of Huygens' Observations

Ordinarily, a beam of light consists of waves whose forces vibrate in all possible directions perpendicular to the direction in which the waves are moving. In Huygens' experiment, when the light waves reached the first crystal, only the forces that happened to be lined up with the grain of the crystal could pass through. The light coming through vibrated in a plane parallel to the axis of the crystal. It was polarized light because only vibrations lined up in one direction were there. The light was plane polarized.

When the waves that had passed through met the second crystal, they again passed right through because the axis of the second crystal happened to be lined up with the axis of the first crystal. The light did not look any different from ordinary light. However, when Huygens turned the second crystal, gradually fewer and fewer vibrating forces of light could get through the axis. The light he saw became darker. When the axis of the second crystal was at right angles to the axis of

the first crystal, no light at all could go through. This led him to identify light treated this way as being special. He called it polarized light. None of this could have happened if light waves were not transverse.

In fact, only transverse waves can be polarized. If you want to find out whether a particular wave is transverse, try to polarize it. That is how scientists found out that sound waves, for example, are not transverse. They are longitudinal. All their particles vibrate in the same direction as the wave is moving. Therefore, they are not interrupted by a polarizing device.

Studying Polarization in the Laboratory

You can study polarization of light with this setup. Use an ordinary source of light. The first crystal that polarizes light is called the polarizer. We cannot see the difference between polarized and ordinary light. The second crystal is used to help us detect polarized light. It is called the first analyzer. When it is held so that its axis is parallel to the axis of the polarizer, polarized light passes through its axis also. The third crystal is used to prove that the light entering it is really polarized. It is called the second analyzer. Its axis is held perpendicular to the axis of the first analyzer. If the light is polarized, it will not be able to pass through the second analyzer. You can change the position of the second analyzer then so that the polarized beam is sent through partially or entirely.

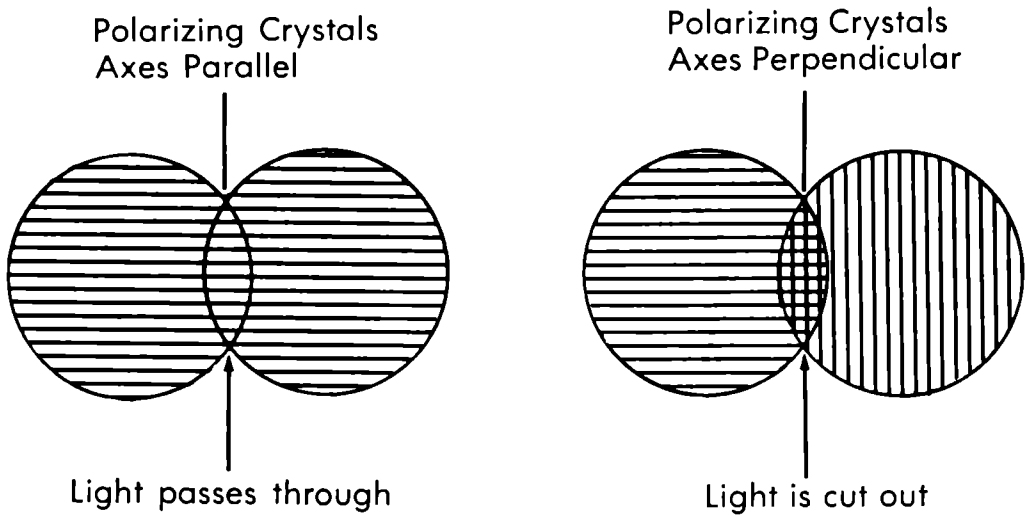


FIG. 31 *Crossed polarizing crystals.*

How Light Is Polarized

Light can be polarized in three ways:

1. By passing light through certain crystals. Quartz, calcite, tourmaline, or artificial Polaroid transmit light only in a single plane of polarization.
2. By reflection at certain angles from smooth surfaces, such as water, glass, etc. This fact is used in the manufacture of sunglasses to eliminate glare. You can test this kind of polarization with your crystal analyzer or a Polaroid filter. There will be one angle at which the light will be completely shut out. You will see darkness. This is the angle of polarization.
3. By the scattering of light by particles in the atmosphere. It is responsible for the blue color of the daylight sky and the orange-red color at sunset. Blue light (shorter wavelength) is scattered more than red. Toward evening, when sunlight travels a longer distance to reach your eyes, a large portion of the blue light of sunlight is removed (polarized) by scattering. If blue light is removed from the spectrum of white light, yellow-orange-red remains. This light, reflected from clouds to you, gives sunset its characteristic appearance. If the earth had no atmosphere, there would be no particles to scatter the sun's light. We would receive no sunlight on earth, and the sky would be black day and night as it is in outer space.

Uses of Polarization

Glare Reduction. In 1928 Edwin H. Land invented Polaroid. It consisted of crystals (iodoquinine sulfate) lined up in parallel formation, embedded in plastic and enclosed between two plastic plates. Changes have been made over the years, but basically Polaroid consists of crystals lined up in parallel formation in one direction and embedded in a sheet of plastic. It is an artificial polarizer.

Sunglasses made of Polaroid are designed to eliminate glare from highly reflecting surfaces. When sunlight is reflected from such surfaces, it becomes partially polarized. The Polaroid in the sunglasses is so set that it cuts this light out while allowing the surrounding ordinary light to enter your eyes. The quantity of light coming from the reflecting

surface to the viewer's eyes is reduced; therefore, glare is reduced.

Stress Analysis for Construction Engineering. Polarized light helps an engineer make decisions about the materials and design of a construction so that the structure will be able to withstand the stresses and strains of time and use. To make this study, the engineer first makes a model of the object out of clear plastic material. He places this model between two Polaroid sheets turned at right angles to each other so that no light can come through. He then uses a machine to exert the same kind and degree of force on the model that the real object will get in actual use. A beam of light is sent through the Polaroid and model setup. Strain shows up as a pattern of bright and dark bands, narrowest and crowded together most closely wherever strain is greatest. The smallest problem areas can be found on the smallest objects, such as gear teeth, by this method. The engineer then has the information he needs to correct the design or change the material to eliminate dangerous areas of stress before construction begins.

Saccharimeter. A saccharimeter is a device used commercially to determine the proportion of cane sugar in a sample of food or other material. When a beam of linearly polarized light (specially polarized by single rays alone) is sent through a solution of cane sugar, the ray emerges at right angles to the direction at which it entered the solution. Its plane of polarization has been rotated to the right by the cane sugar solution. By measuring the angle through which the plane of polarization rotated in a particular sample, the amount of sugar involved can be figured out.

By the close of the 19th century, the wave theory of light was firmly established. It explained diffraction, interference, and polarization. Discovery of polarization gave evidence that light consists of transverse waves. James Clerk Maxwell's electromagnetic theory of light suggested that these transverse light waves were made of electric and magnetic vibrations at right angles to the direction in which the transverse waves were traveling.

SUMMARY

Interference, polarization, and diffraction support the wave theory of light.

Interference

Interference occurs when two sets of waves coming from the same source meet, reinforcing each other if they meet in phase and canceling each other if they meet out of phase. Examples are Newton's Rings, soap bubbles, and oil slicks.

Uses of interference include precision testing of mirrors and lenses and precise measurement of size by means of the interferometer.

Interference effects can be prevented by lens coating.

Polarization

Polarization of light is the process of removing from a beam of light all the vibrations except those in one direction.

Only transverse waves can be polarized.

Light waves are transverse.

The eye alone cannot detect the difference between ordinary and polarized light.

A polarizer of crystal or artificial Polaroid allows only those vibrations of light that are parallel to its axis to pass through.

The analyzer of crystal or artificial Polaroid allows all the polarized light to pass through if its axis is lined up with that of the polarizer. If not, less polarized light passes through. If the analyzer is perpendicular to the polarizer, no polarized light passes through.

Uses of Polarization

1. Glare reduction from highly reflecting surfaces.
2. Stress analysis for construction engineering.
3. Determination of the proportion of cane sugar in a given sample of food or other material.

VII

Visual Perception

Visual perception deals with how we see physically, mentally, and emotionally. Much is known about this phase of science. Still more remains to be discovered. Let us look into it.

Optics

The scientific study of light and vision is called optics. Any instrument associated with light and sight is called an optical instrument. A great variety of lenses, microscopes, and telescopes have been designed and produced to help bring to human view objects too small or distant to be seen. Other optical instruments were invented so that light itself could be studied. Since there is no way for human tissues to preserve what is seen, cameras were invented and the branch of optics known as photography was born.

What Is Meant by "Seeing"?

"Seeing," or visual perception, on the other hand, is a very personal thing. First, it involves all the information available to you in your environment. Second, it involves the use of your eyes to select the information you want or need to "see." Have you ever had a friend suddenly say to you, "Did you see that?"

"No," you answer, "I didn't notice." The essence of "seeing" is noticing, becoming aware.

Third, your eyes must form an image of the object you are looking at. For this, you have a lens plus other structures in each eye along

with the retina, an especially sensitive tissue lining the inner rear section of the eye. From your study of lenses, you realize that the image will be smaller than the object and inverted.

Fourth, the image formed on the retina of each eye is slightly different. Therefore, fifth, each image must be sent to your brain for interpretation. To do this, nerve signals (impulses) representing the image on each retina are sent along the nerve cells in the retina to the larger optic nerve, and then along the optic nerve to your brain. Your brain, which is also nerve tissue, interprets the signals it receives. It superimposes the images it receives from both eyes so that you "see" the single object you were looking at in its true position and size.

Finally, "seeing" involves visual perception, the interpretation your mind (consciousness) gives to the information it receives.

Of course, there is far more information in our environment than any one person can assimilate. That information is lost to us. The loss will be different for each person, depending on three factors: the nature of light itself, the nature of human visual systems, and the interactions between the two. Researchers in the field of visual perception are constantly trying to learn through scientific investigation the particulars of how we see. They even study the kinds of information lost to us. Much has been learned, but there still is so much that is not known. Perhaps you would like to become a scientist who investigates visual perception.

An Interdisciplinary Study

The study of visual perception involves reading and research in many sciences. Here is a list of the contributing sciences together with relevant areas of primary concern. Remember that there is always overlap among the sciences.

Physics—The study of light and optical instruments.
Chemistry—The study of visual pigments in the eye.
Biology–Anatomy—The study of the structure of the eye, other sense organs, and the nervous system, particularly the optic nerve and brain.
Biology–Physiology—The study of the functioning of the parts of

the eye, the sense organs, and the nervous system, particularly the optic nerve and brain.

Psychology—The experimental study of the mental processes and behavior of human beings with reference to light and vision. New methods of recording nerve inpulses and measuring absorption of light by the eye have made important psychological studies possible.

Mathematics—Used here to establish the specific relationships in number, form, and arrangement that exist among factors in each related study.

Experimental Studies

In studying the kinds of information lost to human observers, psychologists have confirmed the following through extensive experimentation:

1. No matter how much work our optic nerve does, it cannot increase the amount of information we perceive about an object beyond what is present on the retinal image.
2. When we try to form a concept or consider a single aspect of an object, we lose all the other information that surrounds that object.
3. Once an image on our retina becomes stabilized, it disappears. It is lost to us. That is why photography was invented.
4. We are extremely insensitive to the level of brightness in our environment. We take little notice of it. It is lost to us.
5. The human nervous system is not equipped to process (handle) all the information available to it and then decide whether to throw it away or use it. Therefore, we seem to select visually those classes of information with items most useful to us. The rest is lost.
6. Our nervous systems detect change in our environment and transmit those items to our brain. We do not pay attention to steady-state conditions in our environment. They are not transmitted to our brain. Steady-state conditions are lost to us.

Scientists have discovered that we "see" things in ways that make sense to us according to our experience, knowledge, and expectations. Some time ago an interesting experiment was performed. It was known that the image of an object formed at the back of the eye is inverted

and that our brain reinverts the image so that we see the object right side up. Scientists wanted to find out whether this ability is inborn or learned. This is what they did.

They provided subjects of the experiment with glasses that inverted everything. The image in the subject's eyes was, therefore, right side up. The brain then interpreted everything as being upside down. After a time, although they still wore the glasses, the subjects reported seeing things right side up. Subjects were then told to remove the glasses. Such confusion! Everything looked upside down again! It took several days for their brains to readjust so that objects appeared right side up. This experiment showed that people interpret the images in their eyes according to their previous experience. They see what they expect to see.

Many studies are now going on to discover how to help people who cannot read because they cannot "see" letters right side up and left to right. Much is yet to be discovered about the relationship between sight and thought.

The Path of Sight

From eye to optic nerve to brain: that is the path of sight. It has a close relationship with other senses. Together with the skin, it brings us information regarding the shape and texture of objects. The balancing mechanism of the inner ear (semicircular canals) plus the balancing mechanism of the brain (cerebellum) plus the activity of our muscles give us a sense of where we are in space. The path of sight allows us to accept or correct the information we receive through these other pathways. In addition, our path of sight allows us to make judgments with limited information. We see a few lines drawn on a canvas and recognize the face it was meant to portray. The gaps are filled in, the picture is completed and organized "in our mind's eye."

The Eye

The eye is a remarkable instrument. It is part of the nervous system. It is a receptor (receiver of stimulation), a sense organ especially sensitive to light. It is protected somewhat by its location in a hard, bony socket in the skull. Salty tears provide moisture and cleansing for the surface

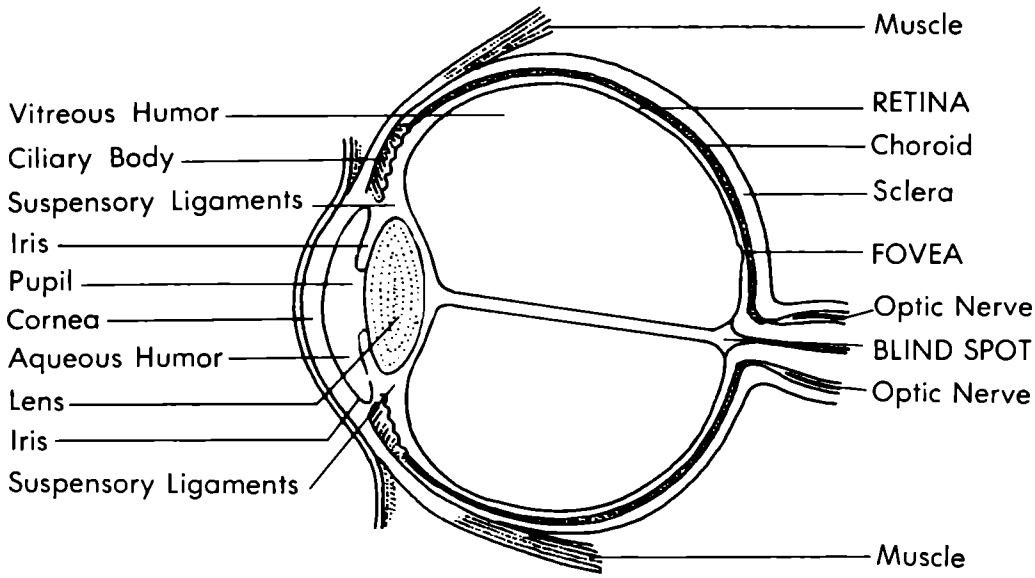


FIG. 32 *Diagram of the human eye.*

of the eyeball and protection against the invasion of bacteria. The eyebrows prevent perspiration from entering the eye. The eyelids spread tears and, together with the eyelashes, keep out dust and foreign objects by the reflex act of blinking. The eyeball is attached to the walls of the socket by three pair of muscles; one pair can roll the eye upward, another downward, and the third from side to side within the socket.

The eyeball itself is nearly spherical in shape, with a diameter of about one inch. It is slightly longer from front to back than from side to side. It is composed of three layers of tissue: the outer sclera, the middle choroid, and the inner retina. Within these three layers are all the structures necessary to make and capture the image of an object. The structures, their descriptions, and functions are listed below.

Structures in the Eye

Structure	*Layer*	*Description*	*Action-Function*
Cornea	Sclera	Clear, circular, convex, transparent tissue in front of the eye.	Allows light to enter the eye.
		Tough, white fibrous, opaque tissue surrounds the cornea and makes up the rest of the outer layer.	

Structures in the Eye (continued)

Structure	*Layer*	*Description*	*Action-Function*
Iris	Choroid	Beneath the sclera except where the cornea is. It has blood vessels and a reddish purple pigment.	Pigment absorbs stray light rays inside the eyeball, thereby preventing reflections that might make images fuzzy.
	Choroid Extension	A colored ring of two sets of muscles surrounding the black opening called the pupil.	Regulates the amount of light entering the eye by contracting or relaxing the muscles to change the size of the pupil opening.
Lens	Suspended from Choroid by ligaments and the ciliary muscles	Crystalline, convex, converging, transparent, elastic.	Causes light rays entering the eye to converge, bringing them to a focus so that a tiny, real, inverted image is formed of any objects we look at. In normal eyes, the image falls on the retina.
Retina	Innermost coat	Lines the inner surface of the eye up to the ciliary muscles. Contains two types of receptors: rods, sensitive to light; and cones, sensitive to color. They are connected to a network of other nerve cells all over the retina that lead to the rear of the eyeball, where they come together to form the optic nerve that leaves from the back of the eyeball.	Provides a place for images to be formed. Special cells (rods and cones) respond to various intensities of light and color that fall on them and send the resulting impulses along the optic nerve to the brain.

Structures in the Eye (continued)

Structure	*Layer*	*Description*	*Action-Function*
Fluids in the Eye	—	Aqueous humor: watery fluid in the space between cornea and lens. Vitreous humor: transparent jellylike fluid between lens and retina.	Help keep the eyeball in shape. Help refraction of light toward the retina.
Fovea	—	A pit in the center of the retina where cones are packed together.	Provides the area of most distinct vision.
Blind Spot	—	The region on the retina where there are no rods or cones. The optic nerve leaves the eyeball from the rear of the blind spot.	The location where the optic nerve exits the eyeball on the way to the brain.

How Do the Iris and Pupil Behave?

The iris is a ring-shaped set of two muscles surrounding the black opening called the pupil. The iris may be colored any shade of blue, green, or brown. The pupil is covered by the cornea. Together, the cornea and pupil form a transparent window that lets light enter the eye. The muscles of the iris enable it to change the size of the pupil.

To find out how these structures behave, take yourself, a hand mirror, and a large flashlight into a dimly lit room. Observe the size of your pupils in the mirror. Go into the closet for a few minutes. Emerge and quickly look at your pupils. Observe how large they have become. While looking in the mirror, quickly shine the flashlight near your face as you observe your pupils. In a matter of seconds, they become very small. You have no control over this reaction. It is an inborn, automatic, reflex act. It helps you adapt quickly to changes in the brightness of your surroundings by allowing more or less light to enter your eye as needed. But this is not enough. The retina also must change its sensitivity to light. When you go from a dark place into a bright one, the retina reduces its sensitivity to light. In a few minutes, you

can easily identify objects in the bright light. When you go from a brightly lighted place to a dark one, your retina increases its sensitivity to light so that you can take the best visual advantage of whatever light is available. It takes from 30 to 40 minutes to adapt newly to a dark place. That is why airplane pilots and crew about to go on night flight duty spend time in a dimly lighted ready-room. Their eyes become "dark adapted."

Why Do the Pupils Appear Black?

Outside light enters the eyes but does not illuminate their interiors. Some is absorbed by the visual pigments (chemicals) in the retinas. The remaining light is absorbed by the pigmented layer of cells behind the receptors, lining the inside of each eye. Very little, if any, light is reflected back into your observer's eyes. The same is true if you look at yourself in the mirror. This absence of reflected light produces the sensation of black for the observer.

Ciliary Muscles and Lens Accommodation

Whether you examine an object close at hand or gaze at an object in the distance, your eyes, if they are normal, will make it possible for images of those objects to be focused clearly on your retinas. This is possible because the ciliary muscle in each eye can change the thickness of the lens and so change its focal length. When you look at a nearby object, your lenses are automatically made thicker by the action of the muscles around them. This decreases their focal length. When you look at more distant objects, your lenses are made thinner, increasing their focal length. They become relaxed. That is why it is advisable to gaze out into the distance from time to time when you must concentrate on close work for long periods of time.

The natural ability of the eye to change the shape of its lens automatically so that clear images of nearby or distant objects can be formed on the retina is called *accommodation.* As we grow older, our lenses become harder and less flexible. Their ability to accommodate for nearby viewing is gradually lost. Most senior citizens see well at a distance but need glasses for close work.

Lens Correction for Common Eye Defects

Defect	*Cause*	*Remedy*
Nearsightedness (nearby objects seen clearly)	The nearsighted eye. The eyeball may be longer than usual, or the lens may be too convex. Light rays come to a focus before they reach the retina. Objects are held close to the eyes.	Eyeglasses with concave diverging lenses. The combination of this diverging lens and the converging lens of the eye makes the light rays from an object converge just enough to bring them to a focus on the retina.

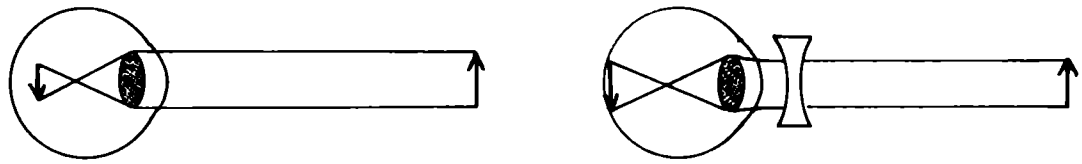


FIG. 33 *The nearsighted eye (cause): The nearsighted eye (remedy)*

Farsightedness (distant objects seen clearly)	The farsighted eye. The eyeball may be shorter than normal, or the lens is not curved enough. Light rays come to a focus behind the retina.	Eyeglasses with convex converging lenses. The combination of this converging lens and the converging lens of the eye causes light rays from an object to come to a sharp focus on the retina.

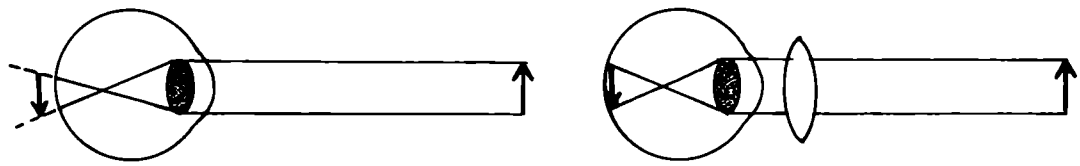


FIG. 34 *The farsighted eye (cause): The farsighted eye (remedy)*

Astigmatism (parts of image are blurred)	Slight irregularity in the curvature of the cornea or the lens. Light rays passing through the irregular areas do not come to a sharp focus on the retina.	Eyeglasses with varied curvature to make up for the irregularities in the eye's lens and/or cornea.

Cataracts

Ordinarily, the lens of the eye is clear and transparent. However, disease, injury, and aging may cause the lens to become progressively more clouded and finally opaque. Little by little, fewer and fewer light rays can reach the retina; those that do are distorted. Hazy vision results. Finally, the lens becomes opaque. No light rays can get through, and the person is blind. The lens that has become opaque is called a *cataract.* When a cataract is removed surgically and replaced by special eyeglasses or contact lenses, the person is able to see. It is very important that the glasses be worn in the correct position on the nose; otherwise, light will not be correctly refracted and will not be brought to a focus on the person's retinas.

Diseases of the cornea

These diseases are very painful and very serious. See your doctor promptly if you have any eye infection or other trouble with your cornea. Corneal diseases include the following:

Infections of bacteria, virus, or fungus
Mechanical injury—tears and scratches
Allergic reactions
Improper moistening
Thickening

If in spite of treatment the cornea becomes opaque, it may be replaced by a corneal transplant. Intensive research has resulted in great success with corneal tissue transplant.

Careers in Optics

Ophthalmologist. This person is also called an oculist. He or she is a medical doctor who specializes in the total care of eyes. He is trained and qualified to diagnose and treat all eye and visual system problems along with general diseases of the body. Since the eye is affected by the general health of the body, the ophthalmologist diagnoses and treats eye problems as part of total health care. As necessary, he prescribes

eyeglasses, contact lenses, medication, surgery, or any other required scientific therapy.

Educational requirements are 4 years of college premedical training; 4 years or more of medical school; 1 year of general medical internship; and 3 or more years of medical training and experience in eye care in hospitals and medical eye clinics. (Adapted from the New York *Times* Supplement "Facts You Should Know About Your Vision" by the Better Vision Institute, from the condensation of a definition by the American Association of Ophthalmology.)

Optometrist. A Doctor of Optometry (OD) is a primary provider of vital health care services who examines, diagnoses, and prescribes specific treatment for conditions of the vision system. He or she examines eyes and related structures to determine the presence of vision problems, diseases, or other abnormalities, using drugs for diagnostic purposes when permitted by state law. As he examines the internal and external structure of the eyes, the optometrist can detect systemic and eye diseases requiring referral of the patient to a physician.

The optometrist treats by prescribing and adapting spectacle lenses, contact lenses, or other optical aids and uses visual training and vision therapy to preserve or restore maximum efficiency of vision.

Educational requirements are 2 to 4 years of college pre-optometric training and 4 additional years of specialized training at an accredited college of optometry. (Adapted from the New York *Times* Supplement "Facts You Should Know About Your Vision" by the Better Vision Institute, Inc., from the definition furnished by the American Optometric Association, Inc.)

Optician. This person is also known as a dispensing optician or ophthalmic dispenser. He or she designs, verifies, and delivers to the intended wearer lenses, frames, and other specially fabricated optical devices upon prescription. (Adapted from the New York *Times* Supplement "Facts You Should Know About Your Vision" by the Better Vision Institute, Inc., from the definition furnished by the Opticians Association of America.)

Educational requirements are: High school graduation; associate degree from a vocational, technical, or community college; and a 3-year apprenticeship in an optical dispensing establishment, including 150 hours per year of related instruction required by the U.S. Department of Labor.

Other Sources of Imperfection of Image on the Retina

Spherical Aberration—This usually refers to a fault in mirrors and lenses with spherical surfaces that causes them not to bring parallel rays striking all parts of them to the same focus. In the human eye, none of the surfaces is perfectly spherical, and the center of the lens has greater refractive power than the edges in some cases and not in others. The shapes of the different surfaces in the eye cause rays from a point source not to meet at a perfect point in some eyes. The imperfection of retinal image that results is called spherical aberration, even though none of the surfaces involved is really spherical.

Random Variation—The light rays from a point source that enter two neighboring parts of the pupil may come to focus in different planes on the retina. This reduces the clarity of the image even in eyes that are considered normal.

Light Scattering—Light is scattered by particles inside the eye liquids and the lenses increasingly with age, making the images formed less and less clear.

Diffraction of Light—We have already discussed the fact that the diffraction of light is a source of image blurriness.

The Retina

The retina is nervous tissue that lines the inner rear surface of the eyeball. Although it is less than 1/80 of an inch thick, it is composed of seven layers of cells, receptors, tiny masses of nerve cells called ganglia, and nerve fibers. The specialized receptors are called photoreceptors. There are two types of photoreceptors, rods and cones. They are found in the seventh layer—the one farthest from the front of the eye, pointing toward the rear surface of the eyeball.

Rods—The rods are long and thin. They are sensitive to light, but not color. They can pick up black, white, and dim light. They are night vision receptors. The edge of the retina contains rods only.

Cones—The cones are short and wide. They are sensitive to color. They are bright-light, day-vision color receptors. The pit in the center of the retina, called the fovea, has a concentration of cones only. Most of the light rays falling on the retina from the lens are focused into this fovea. It is the point of most distinct vision and of color vision.

Of course, we also see "out of the corner of our eyes" because light rays also fall on the area of the retina surrounding the fovea, where rods and cones are found. This kind of vision is called peripheral vision. It is important to us especially in athletic and car-driving activities. It is protective. We don't have to turn our head to be aware of our immediate surroundings.

Cones are not sensitive to color unless the surroundings are bright. That is why on a moonlit night, while there is enough light present to affect our rods so that we can see objects and people, there is not enough to affect the cones so that we can tell what color any of them are. We see everything outdoors in shades of black and white.

Visual Purple—Rods and cones produce visual pigments, which are compounds that change chemically when they are exposed to light. One of these compounds is called rhodopsin or visual purple. In the presence of light, rhodopsin fades. It breaks down into a protein called opsin and a yellow compound called retinene, related to vitamin A. The greater the intensity of light reaching the retina, the greater the decomposition of rhodopsin. The reverse is also true. On this basis, the receptor cells send differing signals to the optic nerve and on to the brain. If your retina has enough vitamin A, rhodopsin is regenerated (formed again) with the aid of extra energy and certain enzymes. Scientists have found that pigment regeneration is more rapid in cones than in rods, but they do not know why.

When bright light fades the visual purple in rods, the rods become insensitive to additional stimulation by light. That is why when you go from a bright room into a dark one at night, you are temporarily night-blind. Later, as the visual purple is regenerated, the rods begin to function again and you see objects in dim light. This is just part of the mechanism of dark adaptation discussed earlier.

Our night vision is relatively poorer than that of animals, because we have proportionally fewer rods. Cats and owls have many rods proportionally. They see well at night. However, owls have no cones, so they are day-blind.

Measuring the Retinal Image

The ophthalmoscope is a simple optical instrument used for the examination of the living eye. It enables the doctor or researcher to place

his own eye close to the path of the light entering the subject's eye without blocking the light or his view of the subject's pupil. A corrective lens is adjusted to match up the refractive power of the scientist's eye with that of the subject. The entering light falls on a part of the subject's retina. Some of the light is reflected from the retina along paths that are only slightly different from the incident paths. Reflected light emerges from the pupil. Half of it passes the mirror and goes directly into the scientist's eye, creating an image of the selected portion of the subject's retina on the scientist's retina. His brain interprets what he sees. Not only can he study retinal images, he can also observe and evaluate the condition of the subject's circulatory system by observing the tiny capillaries in the retina of the eye. Doctors do this when they examine a patient.

Optical Illusions

When your eyes fool you, when what you see is not a true situation as determined by objective measurement, you have an optical illusion. There are many such in our world of perception.

If we camouflage a fault in our physical form by wearing specially designed clothing; if we disguise a set of unmatched windows with a screen or drape; if we hang a mirror on the long wall of a narrow room; if we cover an open trench with the boughs of trees; if we apply makeup to our faces; if we put scenery on a stage, we are seeking to create an optical illusion for someone else. Magicians do it all the time.

Look at this picture. Do you "see" the lovely young girl? Or is it a tired old woman? Or does the picture shift back and forth from young girl to old woman? Just a few lines on a piece of paper create this illusion for you, depending on "how you see it"—your visual perception.

When you sit on a train in a railroad station impatiently waiting for it to move, and the train next to yours begins to pull out first, you seem to see your train moving—but in the opposite direction. You cannot feel it moving because it is not moving. Your eyes have fooled you.

One evening, you look up at the moon. It appears to be racing across the sky. You are experiencing an optical illusion. In reality, it is the clouds beneath the moon that are moving. Astronomy explains many optical illusions. You may want to look into this subject.

COURTESY MRS. LUCY D. BORING

FIG. 35 *The Wife and the Mother-in-law (from Boring, Langfeld and Weld,* Foundations of Psychology, *John Wiley and Sons).*

When we look at a good drawing, painting, or photograph, the objects or scenes shown look "real" to us. They appear to have length, width, and depth—three dimensions—and seem to have a reasonable distance relationship even though they are pictured on a flat, two-dimensional surface of paper or canvas. The techniques for representing these illusions of depth, distance, and dimension are called perspective transformations. Perspective in our real, three-dimensional world is also an optical illusion. We know, for example, that the rails of railroad tracks

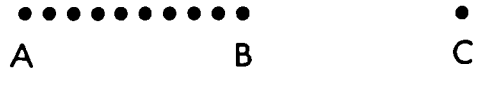


FIG. 36 *Which distance is greater: A to B or B to C?*

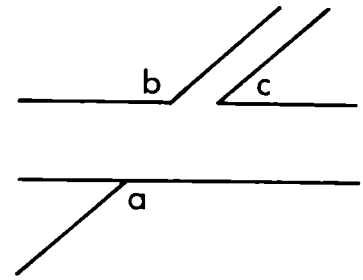


FIG. 37 *Is line* a *an extension of line* b *or line* c?

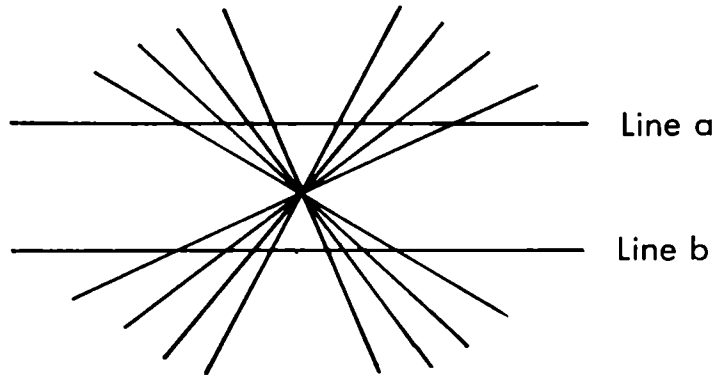


FIG. 38 *Are these lines parallel?*

are parallel to each other. Yet when we look out into the distance, they appear to converge at a point far away. If we photograph these tracks, the picture will show them as we see them—in perspective—an optical illusion.

Then there is a group of optical illusions involving geometric patterns—points, lines, and angles. Try these well-known examples.

Here is an example of an optical illusion based on angles. Look at the gas gauge needle while sitting next to the driver in a car. Move into the driver's seat and look again. What happened? If you first saw the needle at "Empty," you probably saw it registering 1/4 full from the driver's position. This special kind of optical illusion is called parallax. For accuracy, always read meters and scales "head on" and at eye level.

In spite of a century of research, science has not found out why we see geometric optical illusions as we do.

Aftereffects of Motion

Have you ever stared out of the window of a moving train, watching the scenery seem to rush past you toward the rear? When the train stopped, the scenery seemed to move forward, in the opposite direction. This common experience is an aftereffect of motion.

Try this at home. Turn the vertical hold of your television set away from its proper position so that the picture drifts vertically downward. Stare at the screen for a few moments. Correct the vertical hold. The picture will seem to drift upward, in the opposite direction, for a few moments. After making many studies, psychologists concluded that a viewer of movement visually adapts to the first stimulus, and when it is removed the reverse perception takes place. This phenomenon is called the aftereffect of motion. It is another trick the eye plays.

Persistence of Vision

Images stay on the retina for about 1/16 of a second. This ability allows us to see smooth, steady movement in motion pictures. How? Sound films show you 24 frames per second. Each frame is really a still picture, slightly different from the one before it. Together, these frames record the step-by-step changes in position of the objects as they move through the story. When the film rolls, your eyes retain each picture 1/16 of a second, but before that time has passed, the next frame is shown (1/24 of a second). The speed with which the pictures move, plus your persistence of vision, allow you to see the smooth movement of people and objects in a movie.

How We Perceive Color

Over one hundred years ago a hypothesis was formulated which said that there are three kinds of cones in the retina; one sensitive to red light, one to green light, and a third to blue light. When all three kinds of cones are stimulated, the person receives the sensation of white light. When yellow light shines on the cones, it stimulates the red-sensitive and green-sensitive cones. Therefore, when red and green light shine into the eyes of a person, he or she has the same sensation as when pure yellow light shines.

Recently, however, instruments have been developed to measure the sensitivity of cones to light. Scientists have found that there really are three different kinds of cones, each sensitive to a different range of colors but most sensitive to one. One kind of cone is most sensitive to green, another to blue, and a third to yellow. Cones with peak sensitivity to yellow are strongly sensitive to red, whereas the other cones are less sensitive to red. The color sensation you experience depends on the combination of responses of all three cones to the light reaching your eye.

Color Blindness

Some people perceive red as green and green as red. They are red-green color-blind. Some people can see only black, gray, and white. They are color-blind. It is estimated that one man in ten and one woman in one hundred is color-blind in some way. This condition is inherited.

Color Naming Vs. Identification by Wavelength

We know that each shade of color has its own wavelength, determined precisely by scientific measurement. Visible light waves are conveniently measured in nanometers (nm). One nm equals one billionth of a meter. When we use, for example, the word "yellow" to refer to a color, do we mean light yellow, dark yellow, yellow-green, or yellow-orange? No one can know for sure. If, on the other hand, we refer to yellow of wavelength 579 nm or 599 nm, we are referring to very specific yellow lights with specific frequencies and properties. Scientists must use the wavelength method of color identification; designers, painters, weavers, and decorators can match desired color swatches with special color names.

Experiments With Color Identification

Some years ago the American physicist Edwin H. Land, inventor of Polaroid and the Polaroid Land Camera, took a pair of photographs of colored objects using ordinary black and white film in each of two cameras. In front of each camera, he placed a different colored filter; for example, red for one and yellow for the other. When the films

were developed they showed up in tones of gray with no color. He then put each film into a separate projector with a color filter in front of each and projected the two images so that one fell on top of the other on the screen. To everyone's surprise, the picture on the screen appeared in full natural color, showing all shades of color of the original objects.

This experiment made scientists think for the first time that somehow the eye and brain must work together to get the colors from the objects by comparing the two images, one of shorter wavelength and the other of longer wavelength, taking an average, and producing a whole array of color sensations.

Later on, another scientist used yellow light only, one beam with a wavelength of 579 nm and another of 599 nm. He projected two slightly different black-and-white slides of the same scene, one on top of the other on a screen. Viewers "saw" red, blue, and brown objects in the superimposed picture as well as yellow.

Again, this showed that the sensation of color is interpreted by the brain. It does not depend solely on the wavelengths present but also on the ability of the brain to distinguish between the longer and shorter ones, seen as blue or violet. The longer wavelengths stimulate the yellow-sensitive cones more than the others, and the shorter wavelengths stimulate the blue-sensitive cones more than the others. The resulting impulses are sent to the brain for averaging and interpretation.

Much experimentation is going on in this field. Much is yet to be discovered about how we perceive color.

Color of Opaque Objects

The color of an opaque object is the color of the light it reflects to your eyes. When white light shines upon an opaque red object, such as a piece of red construction paper, the red paper reflects the red part of the white light and absorbs practically all the other colors of the spectrum of white light. Green leaves appear green in the presence of white light because they reflect the green part of white light and absorb almost all the other colors of white light.

A blue object illuminated by white light appears blue. It reflects the blue wavelengths and absorbs the remainder of wavelengths in white light. If the blue object is illuminated by blue light, it will reflect blue

light and appear blue. But if the blue object is illuminated by any other color of light, it will absorb almost all the light falling on it, reflect no light to your eyes, and therefore appear black.

A white opaque object reflects whatever color of light falls on it. It appears white in white light, red in red light, green in green light, yellow in yellow light, etc. It takes on the appearance of the color of light it reflects.

Color of Transparent Objects

The color of a transparent object is the color of the light it transmits (lets through). If white light is passed through a piece of red glass, the emerging light is red. If a beam of white light passes through a piece of green glass, the emerging beam is green. Generally speaking, the color of light that passes through a piece of glass is the color of that piece of glass. All colors that do not pass through the glass are absorbed by it. If red light shines on green glass, it is absorbed and no light comes through. Therefore, in cases of transparent objects, the color we see is the color of light that the object transmits.

Mixing Colored Lights

Scientists took three projectors and shined monochromatic (single-wavelength) red light from one, monochromatic blue light from another, and monochromatic green light from a third. They allowed these colored light beams to overlap on a white screen. The center, where the three overlapped, appeared white. Where red and green lights overlapped, they saw yellow. It looked like monochromatic yellow even though no yellow light was shining on the screen. Where green and blue lights overlapped, the color sensation called cyan (blue green) was produced. When blue and red lights are added, a color sensation called magenta is produced. It does not appear in the spectrum of white light. If you vary the intensities of these lights as you combine them, you can make many different color sensations in your mind's eye.

Red, green, and blue are called the *primary colors of light* because the sensation of most of the other colors of the spectrum of white light can be produced by adding together the right amounts of these three colored lights. Yellow, cyan, and magenta are called the secondary

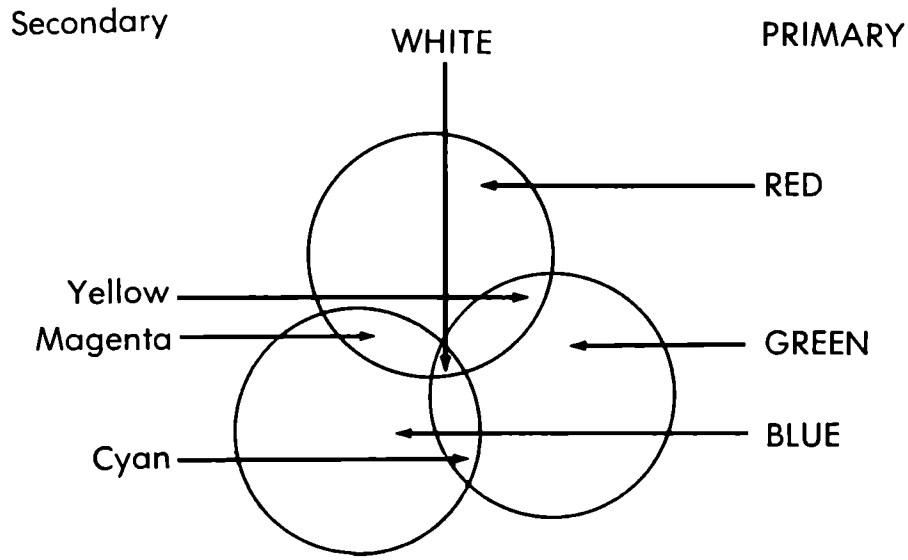


FIG. 39 *The addition of colored lights.*

colors of white light. They result from the mixing of two of the three primary colors. Whenever colored lights are mixed, colors are added.

Color Television

Your color TV set works on the principle of mixing the three primary color lights. However, the colors on the TV screen are next to each other, not on top of each other. The screen of the TV tube is painted with thousands and thousands of phosphor dots lined up in groups of three. When you turn on the set, the phosphors are activated by electron beams. One dot glows blue, the next green, the next red, and so on. When the entire phosphor dot plate is glowing, you see white. If electron beams strike red and green dots, you see yellow. If they don't strike red or green, you see a shade of blue. Various shades of color are produced by varying the intensity of the electron beams that are aimed at the phosphor dots. Mixing colored lights by addition is the principle behind the functioning of a color television set.

Afterimages

Afterimages are produced when some of the eye's cones are fatigued. If you stare steadily at a bright red object in bright light, count slowly to 100, and then look away to a white wall, you will see the object's

shape on the wall but it will be colored blue-green (cyan). Try this experiment, staring at any brightly colored object in bright light. The color you see on the white wall will always be the complement of the object's color. Complementary colors are two colors of light that, when combined in proper intensities, give you the sensation of white light. Red and cyan light, blue and yellow light, green and magenta light are each complementary pairs. While you were staring at the red object, your blue- and green-sensitive cones had a rest. The red-sensitive cones became weary. When you looked away, the rested cones took over and you saw a blue-green image. That is how scientists explain the phenomenon of afterimages, another of the tricks our eyes play on us.

Mixing Pigments

Mixing paints (pigments) is not the same as mixing light of different colors. If you mix blue and yellow paints and view the result in white light, you will see green. What is the relation of pigments to white light? What is the relation of all of this to your perception of color? The blue paint alone must reflect blue light, but it may also reflect the colors of light on either side of blue in the spectrum of white light. These would be violet and green. Blue pigment absorbs red, orange, and yellow. The yellow pigment reflects yellow, some orange, green, and red, the colors on either side of it in the spectrum of white light. The yellow pigment absorbs blue and violet light. When blue and yellow pigments are mixed, blue absorbs red, orange, and yellow (r o y), and the yellow pigment absorbs blue and violet (b v). The only spectral color left is green. So it is that when colored paints are mixed, color is subtracted. In this case, the left-over green is reflected to your eyes. Your green peak cones are stimulated. Impulses are sent to your brain and you perceive green to be the color of the paint. The study of the mixing of colored lights and that of pigments is very complicated. The explanations presented here are meant to give you the basic idea of each process. Color perception is under constant study by physicists and psychologists as well as artists.

Light and Art

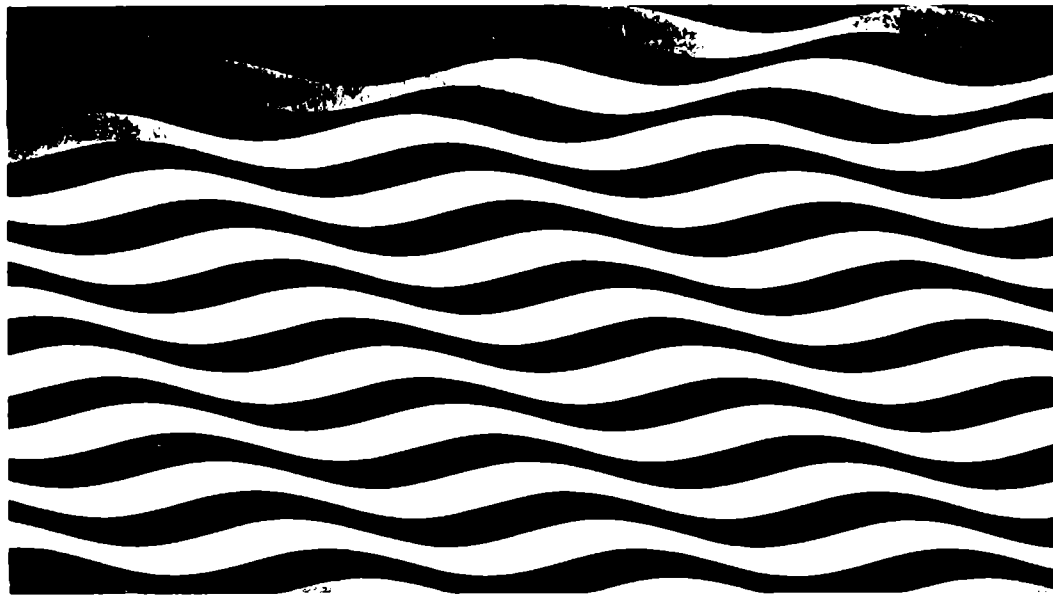
Light, shadow, and color are studied and used by all artists who create drawings, sketches, and paintings as their works of art.

In the 19th century there lived an unusual young painter named Georges Pierre Seurat (1859–91). His artistic style was based on the scientific theories of color and optics of his time. He originated a new impressionist (neo-impressionist) style of painting called pointillism. Instead of using brush strokes of color, he placed multitudes of tiny dots of color side by side as he carefully created a particular painting. He so planned the placement of the colored dots that when viewed from a distance they would fuse in the viewer's eye, creating the effect of light glowing through mixed and gently blending colors and tones. He even added frames painted with the dots so placed that color and tone contrasts would end up equal at every point around the painting. He worked as if he were following a formula. As an artist, however, he added to this precision of method, which he called "my method," his personal sense of style and composition as well as his recognition of the odd and humorous in the human situation. He lived only thirty-two years; but his innovative use of the science of light and color to express his inner vision of art became the inspiration for the op art movement in 20th-century modern art. One of the most beautiful examples of Seurat's work, a picture in color called *Fishing Fleet at Port-en-Bessin, 1888,* can be seen as a painting at the Museum of Modern Art in New York City or as a picture in the elegant art book *Fine Art Reproductions, Old and Modern Masters,* published by the New York Graphic Society, Ltd., Greenwich, Conn.

Op art means optical art. It is a kind of abstract art that became important in the middle 1960's. It is also called retinal art or perceptual abstraction. In 1965 an exhibition of op art called "The Responsive Eye" was given in the Museum of Modern Art in New York City.

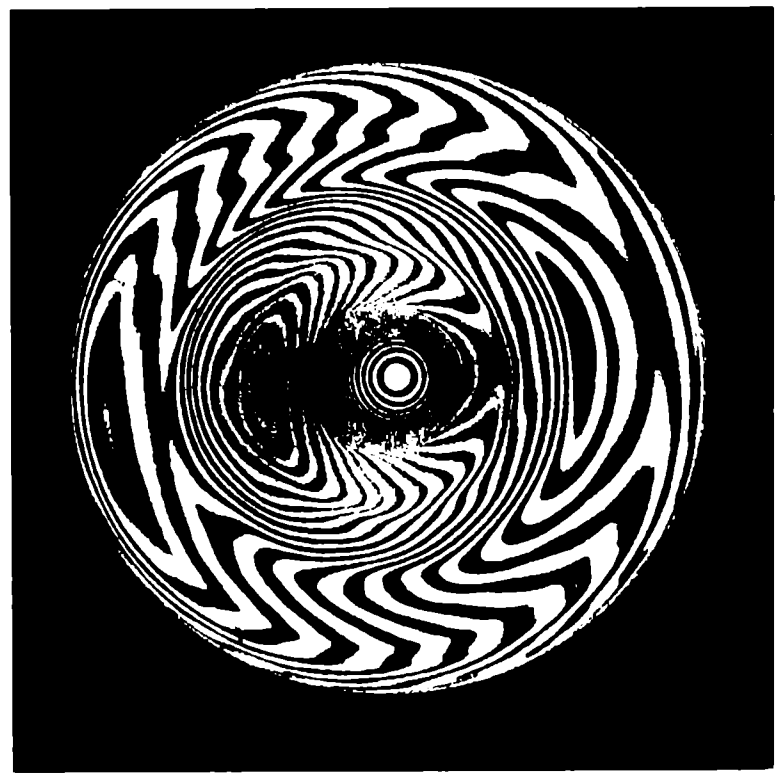
The op art movement had its roots in Seurat's work, but it is far more impersonal. It features designs, not people. Op art resulted from an increased interest in and knowledge of science and technology on the part of young artists. They use a number of perceptual effects. For example, they create the effect of movement where none really exists.

If a square of red and a square of green of equal size, value (lightness or darkness), and intensity (brilliance of color) are placed side by side and you look at them for a while, the colors will seem to vibrate. Imagine how a picture that has several brilliant colors next to each



ALBRIGHT-KNOX ART GALLERY, BUFFALO, N.Y. GIFT OF SEYMOUR H. KNOX

FIG. 40 *"Drift No. 2" by Bridget Riley. Parallel lines seeming to create movement.*



STAEMPFLI GALLERY, NEW YORK

FIG. 41 *"Lens Picture 1962–64" by Karl Gerstner; plastic lens and transparency of concentric circles, 28" by 28". Use of the moiré principle.*

other will appear to vibrate! It seems that the eye has difficulty focusing on two or more competing colors at the same time.

Pulsating and moving effects are produced when various groups of closely placed parallel lines form the op art picture.

Moiré effects are used. Lines crossing at a slant appear to blend at the crossing point and move away from each other farther on. Beautiful effects of shifting movements can be made to seem to occur with this technique.

Sometimes op art uses color afterimages and distortions caused by retinal fatigue. These were discussed earlier.

Sometimes color interaction is used. This results when certain colors are placed next to each other. The color of an object appears to change depending on the colors that border it. Interesting colored shapes are so arranged by the artist that the viewer experiences unusual visual effects resulting from color interaction among these shapes.

Sometimes, op artists create patterns and "invisible paintings," in such closely related shades of color that the entire canvas seems to be made of only one color.

Finally, op art paintings, reliefs, and other compositions have been created on corrugated surfaces so designed that as the viewer walks by them, their composition seems to change.

Appreciation of pointillism and op art depends upon our visual perception of light and color.

SUMMARY

Visual perception deals with how we see physically, mentally, and emotionally. "Seeing" involves:

1. All the information in the environment.
2. Use of the eyes to select desired information.
3. The formation of an image of the object in the viewer's eyes.
4. The transmitting of the image in the form of impulses from each eye along the optic nerve to the brain.
5. The fact that the image from each eye must become one representing the object in proper size and proportion.
6. The interpretation the mind gives to the information.

Visual perception is an interdisciplinary study.

The Structures of the Eye and Their Functions

Cornea—Allows light to enter the eye.
Iris—Regulates the amount of light entering the eye by changing the size of the pupil.
Lens—Refracts light rays entering the eye so that they will come to a focus on the retina of the healthy eye.
Retina—Provides the place for images to be formed. Contains rods sensitive to light, cones sensitive to color, masses of nerve cells called ganglia, and capillaries.
Fluids in the Eye—Help maintain the shape of the eyeball and refract light toward the retina.
Fovea—Provides the area of most distinct vision.
Blind Spot—The place where the optic nerve leaves the eyeball on its way to the brain. Since no rods or cones are present, no sight is possible.

Accommodation is the natural ability of the lens of the eye to change its shape automatically so that clear images of nearby or distant objects can be formed on the retina.

Eye Defects and Correction

Nearsightedness—Corrected by diverging (concave) lenses.
Farsightedness—Corrected by converging (convex) lenses.
Astigmatism—Corrected by appropriately curved lenses for the case.
Cataracts—Corrected by surgical removal and replacement by lenses in eyeglasses or by contact lenses.
Corneal diseases—Treated by medication and, if necessary, by removal followed by corneal transplant.

Careers in Optics

Ophthalmologist—M.D. specializing in eye problems.
Optometrist—O.D. specializing in eye problems. He or she is not a physician.
Optician—Grinds and dispenses lenses on the prescription of an ophthalmologist or optometrist.

Other Sources of Image Imperfection on the Retina

Spherical aberration and random variation produce fuzzy images. Light scattering and diffraction produce unclear images.

The Retina

Rods—Cells sensitive to light; night vision receptors.

Cones—Cells sensitive to color; bright-light day-vision color receptors. Three kinds of cones: peak yellow-sensitive, peak blue-sensitive, and peak green-sensitive.

Visual purple—One of the visual pigments of the eye; a chemical compound bleached by light and restored later; helped by sufficient supply of vitamin A.

VIII

Light for Telephone Talk

"Hi, Sue! How are you? So glad I found you home." So begins your half-hour telephone conversation with your friend. How happy you are for the speed and convenience of the telephone! Of course, you do not think too much about how your voice and speech are transmitted. Electrical pulses, traveling along copper wires and radio waves have been doing the job rather well. However, scientists have been concerned with the problem of making prompt and efficient telephone service available to an ever-increasing population wanting to use the telephone.

Scientists thought they would try using light as a transmitter of voice and speech. After all, light in the form of bonfires, flashing lights, or signal lamps has always been used to send signals over short distances through the air. But for long-distance transmission of speech and voice signals, they would need a special kind of light and a special kind of wire.

Research to develop these items and put them together successfully has taken many decades. According to scientists, we can now expect that during the 1980's telephone conversations will be carried by light over special optical wires. The achievements responsible for this possibility are:

1. The invention of the laser, its refinement and miniaturization (reduction to very small size), giving scientists a very narrow, powerful beam of light that can be controlled and sent over long distances without diverging.
2. The production and improvement of glass fibers so pure that they can transmit light over long distances and so thin that they take up much less room than an equal number of copper wires. Corning

Glass Works is given credit for this development, called fiber optics.

3. The development of methods of putting fiber optics into present-day telephone systems and making them work together. Engineers at Bell Laboratories are given primary credit for this accomplishment.

Let us examine the particulars involved in the development of each of these important contributions.

The Laser

The laser is a device that produces coherent light.

Incoherent vs. Coherent Light. Light from an ordinary incandescent light bulb is disorganized. It is incoherent. It is composed of light waves

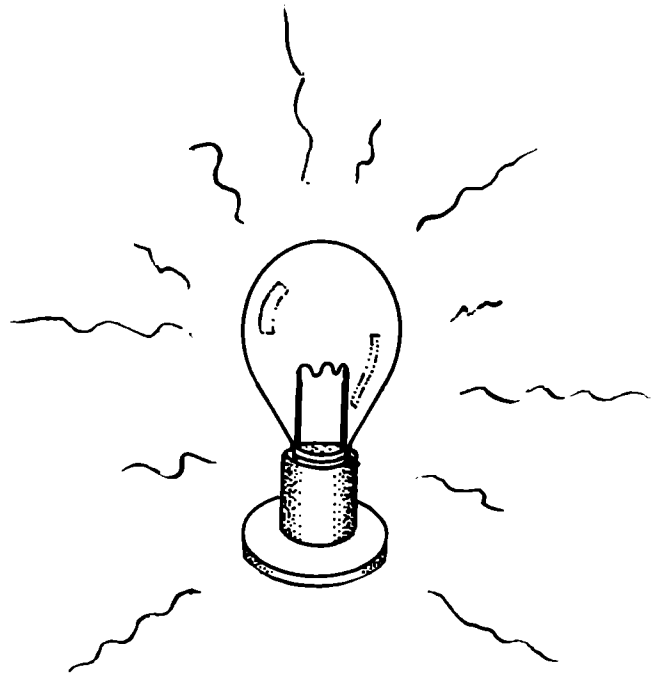


FIG. 42 *Incoherent light.*

of different wavelengths emitted in short bursts of energy at different times, in different directions, and largely out of phase with each other. The waves, therefore, cannot reinforce each other to any great extent, so their energy becomes diffused rather than concentrated.

Coherent light, on the other hand, is highly organized. It is composed

of light waves of the same single wavelength, emitted in one direction, with waves in phase with each other, reinforcing each other to produce a highly concentrated (intense) beam of monochromatic (single-color) light.

FIG. 43 *Coherent light.*

Development of the Laser

The development of the laser, like most scientific discoveries and inventions, is based on an accumulation of related scientific ideas, theories, and designs contributed by the thought of many scientists, little by little, over the years.

In 1887, while Heinrich Hertz was experimenting with the electromagnetic waves we now call radio waves, he discovered that ultraviolet light helps electric charges escape from the metal terminals (ends) of an open-ended wire in a circuit.

Other scientists discovered that a negatively charged metal plate lost its charge when ultraviolet light was shone on it, but a positively charged plate did not. Electrons had not yet been discovered.

In 1897 electrons were discovered by J. J. Thompson, a British physicist. They were negative charges much smaller than the smallest atom. They are parts of each atom.

It was recognized that light shining on a metal surface causes electrons to be emitted. This is called the *photoelectric effect.* A photoelectric cell is the modern device that sets up a current (flow of electrons) when light falls on it. We call it the "electric eye."

In 1900 Max Planck published his *Quantum Theory of Light.* Planck showed that the behavior of electrons is closely tied to the production of light. He defined a quantum as a package of energy that a source of electromagnetic waves possesses, can give off, or absorb. He worked with objects that oscillate (move back and forth). He said that an oscillator could have 1 quantum, 2 quanta, 3 quanta, or any whole number of quanta of energy. The size of a quantum is equal to its frequency multiplied by a special number he developed, called Planck's Constant.

When an oscillator absorbs or radiates energy, it does so only in whole-number multiples of quanta. Later experiments showed that light energy behaves like the energy of oscillators.

In 1905 a quiet young clerk in Switzerland explained the photoelectric effect. He did not publish his explanation until 1916, but what he said made the most critical scientists think favorably of the Quantum Theory of Light. That man, of course, was Albert Einstein. In 1921 he won the Nobel Prize for his explanation of the photoelectric effect in terms of quanta of energy. The world knows Einstein for his Theory of Relativity, but for that he did not win a Nobel Prize. In simplified terms, this is what he assumed, said, and did regarding the photoelectric effect:

1. Light reaching the metal surface must come in the form of packets of energy.
2. A packet of light energy he called a photon rather than a quantum.
3. The energy of a photon can be absorbed by an atom at or near the surface of the material struck by the photon.
4. One of the electrons in that atom absorbs that photon (a packet of light energy).
5. The additional energy the electron gets by absorbing the photon may be just enough to push the electron right out of the metal.
6. The higher the frequency, the greater the energy of that one photon. If the frequency is too low, no electron can be pushed out of the metal. There would not be enough energy given to the electron to enable it to escape.
7. If you consider light as a whole, the greater the frequency of the photons, the greater the energy of the escaping electrons.
8. The brighter the light, the more photons of equal energy are delivered, the more electrons escape, but each electron will have the same amount of energy as every other escaping electron.

Niels Bohr tried to visualize an atom. He thought electrons move in orbits called quantum orbits. He assumed that:

1. Electrons usually exist in particular orbits in an unexcited state.
2. When an electron occasionally jumps from an outer to an inner orbit, it loses energy in the form of a single radiated photon. Bohr's model of the atom had to be abandoned. Quantum orbits came to be considered as energy levels.

In 1914 the German physicists James Frank and Gustave Hertz studied mercury. As a result, they said that electrons in atoms could absorb energy and move to higher energy levels when the quanta were large enough. From their experiments, they concluded that the mercury radiates a quantum of the same size that it absorbs.

There all these pure scientific ideas remained until 1951, when Charles H. Townes, then a physics professor at Columbia University, tried to solve a scientific problem involving microwaves. He wanted to find ways to extend the range of microwaves to include even higher frequencies than they normally do. He could then increase the band of frequencies usable for radio and television communications. More information could be sent out on these microwaves, which would be coherent. Thinking over the relevant science then known, he came up with this idea: Take molecules of a substance in a low energy state, as they usually are. Create the condition (called pumping) where an abnormally large number of molecules become high-energy molecules. Stimulate them to emit their energy by using microwaves to "give them a push." This is called *amplification.* Then feed back some of the emitted radiation into the device again to stimulate other molecules to emit radiation. The device is a resonating chamber, and it would resonate at the proper frequency.

He built a small metal box and used ammonia gas. When he beamed microwaves on the device, the molecules became excited. One excited molecule dropped to its normal state and emitted a 24,000-megacycle photon. That hit another molecule, made it drop to the normal state and in turn emit a second photon, and so on, producing millions of photons, lined up parallel to the axis of the resonating chamber. The energy was allowed to flow out of the chamber along a wave guide, forming a steady stream of microwaves. Three years and many experiments later, Townes and his colleagues had created the *maser,* an acronym for what it does and how: *M*icrowave *a*mplification by *s*timulated *e*mission of *r*adiation. For this he won the Nobel Prize in physics in 1964, sharing it with two Russian scientists, A. M. Prokhorov and N. G. Basov, who had contributed to its development. Many forms of masers were developed and are used. The invention of the maser sparked further scientific speculation.

Scientists wondered whether they could produce an optical maser. Could the principles of a maser be applied to frequencies of light that

are thousands of times greater than those of microwaves and to wavelengths that are thousands of times shorter?

In 1958 Dr. Townes and Dr. Arthur L. Schawlow published a paper defining the conditions under which coherent light could be produced. Many scientists tried to be the first to build a device that would deliver coherent light.

In 1960 Dr. Theodore H. Maiman, a research physicist with the Hughes Aircraft Company, announced that by using a man-made ruby

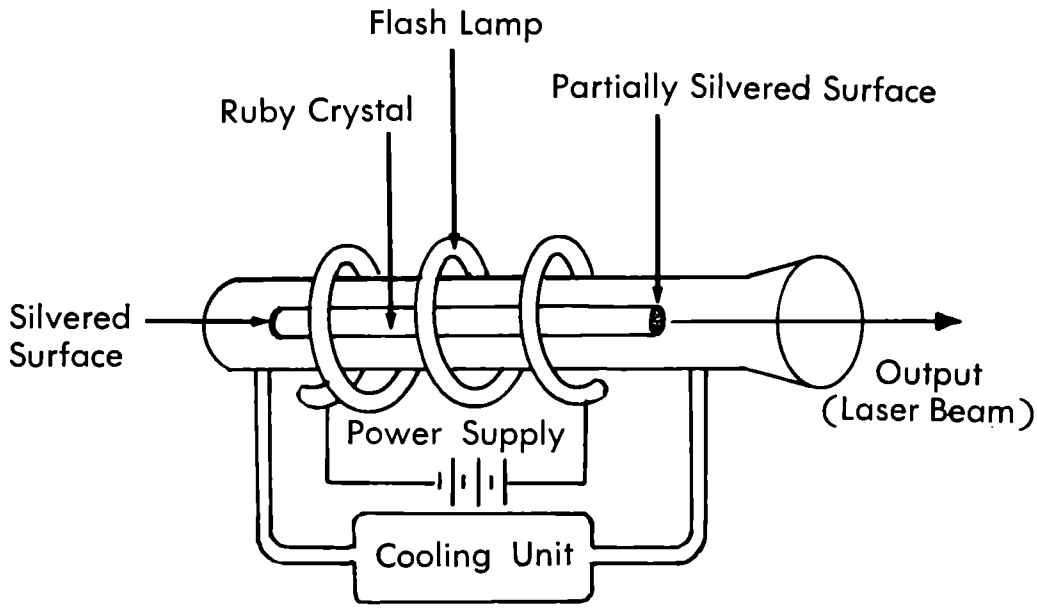


FIG. 44 *Diagram of a ruby laser.*

crystal he had succeeded in producing coherent light, narrow-beamed, powerful, and purer than any ever seen before. Dr. Maiman named his device a *laser,* an acronym for what was done and how it was accomplished: *l*ight *a*mplification by *s*timulated *e*mission of *R*adiation.

This is how it worked. The ruby crystal is aluminium oxide with some chromium atoms replacing some aluminum atoms. Chromium atoms absorb green and blue light, giving ruby its red color.

1. Chromium atoms are usually in the normal unexited state (ground).
2. When the current flows through the flashlamp, it delivers pumping energy. This raises chromium atoms to a higher energy level. Population inversion results. There is a larger population of excited atoms.

3. Some of the excited atoms drop back to the normal ground state, releasing photons.
4. The photons emitted parallel to the axis of the crystal bounce back and forth from end to end between the two mirrors, bumping into other atoms, stimulating them also to emit photons in phase and coherent. More and more photons are released in this way. Photons not in parallel escape or are absorbed by the crystal.
5. Finally, a powerful coherent beam of light energy (photons) comes out through the partially silvered, partially transparent mirror.

This invention merely demonstrated that laser action was possible. Other lasers were devised to assure a steady stream of this powerful coherent light. Solid state forms, optically pumped lasers, gas lasers, semiconductor types, liquid lasers, injection lasers, and chemical lasers were some of the variations produced for different purposes. Improvements were made. Lasers were made smaller and smaller (miniaturized) so that they would produce and emit a beam of coherent light narrow enough to be sent along hair-thin optical fibers.

Optical Fibers

Optical fibers are made of glass or plastic. In the optical telephone system, glass fibers are used. You may remember that a very thin beam of light can travel by a series of internal reflections from one end of a glass fiber to another, no matter how the fiber is curved or bent. The fiber consists of a central core surrounded by a cladding (covering) with a refractive index slightly less than that of the core. The place where core and cladding meet acts like a mirror, totally reflecting any light ray that strikes it at an angle greater than the critical angle. Hundreds of such reflections occur in each foot length thousandths of an inch in diameter. To be able to transmit light over long distances, the glass fibers must be very pure. Engineers are still trying to find more efficient ways of splicing these very thin fibers of pure glass.

The use of glass "wires" offers advantages over the use of copper wires. Glass fibers do not "leak" light. It is totally reflected internally. Copper wires do leak electricity, and sometimes this causes cross-talk and static on present telephone lines when signals of one line interfere

with those of a neighboring line. Glass fibers in an optical telephone system will eliminate this nuisance. One such system is being field-tested in Atlanta by Bell Laboratories.

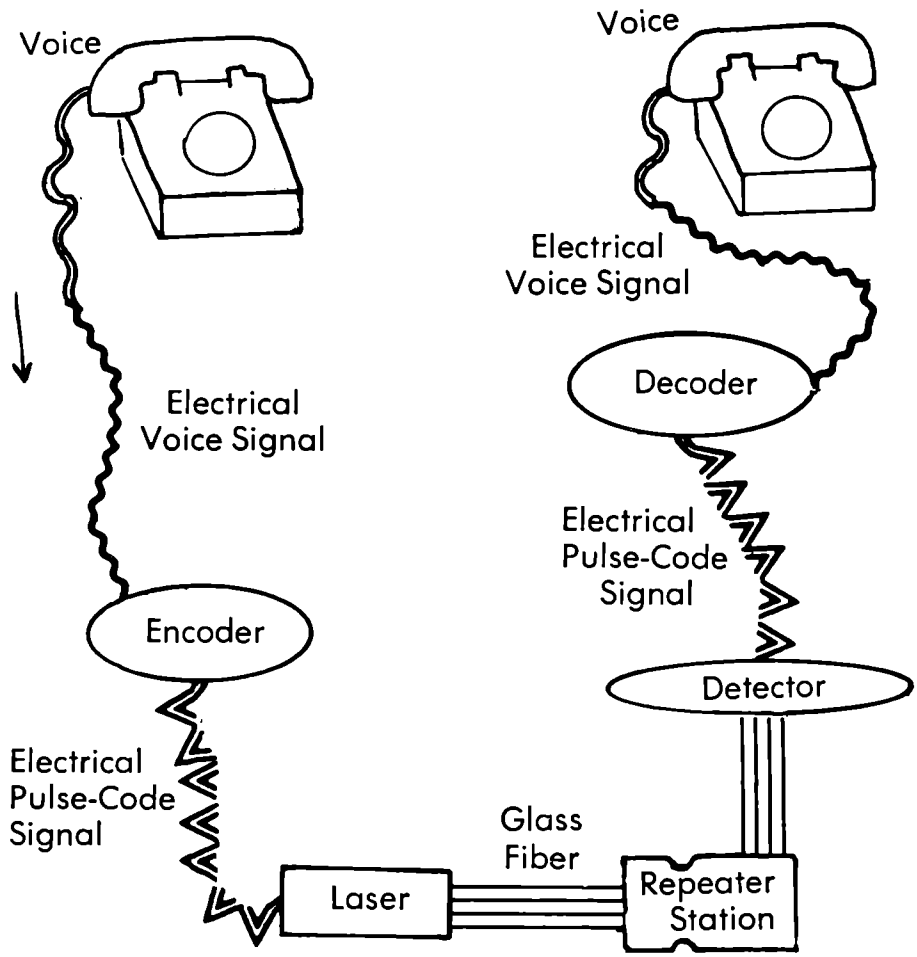


FIG. 45 *Basic parts of an optical telephone system.*

Integrating Fiber Optics into the Telephone System

If there was ever to be developed an optical telephone system, it was absolutely essential that components be miniaturized. Scientists produced ultra thin glass tubing for "wires." They miniaturized the laser so that coherent light beams would be narrow enough to enter and travel along the glass "wires." They are still working to develop integrated optical circuits to perform switching functions successfully.

How the Optical Telephone System Works

1. Sound waves produced by your voice and speech enter the telephone microphone and are changed into electrical' signals.
2. These signals pass through an encoder, which changes the signals into pulses.
3. The pulses switch a laser on and off according to your speaking pattern. This interrupts the light beam coming from the laser and going into the near end of a glass fiber. The light beam travels along the glass fiber in a series of pulses until they reach the photodetector, which picks them up.
4. The photodetector changes the light pulses back into electrical pulses.
5. The electrical pulses move into a decoder, where they are translated into an electrical signal.
6. The electrical signal enters the receiver and vibrates the diaphragm in the receiver, thereby reproducing the voice and words that were sent out in the first place over the microphone.

The story of the optical telephone system has just begun.

SUMMARY

To develop an optical telephone system, three achievements were necessary:

(1) The invention of the laser; (2) the development of fiber optics; and (3) the integration of fiber optics into the telephone system.

Incoherent light—from an incandescent light bulb—is disorganized. Light waves of different wavelengths are emitted in short bursts at different times; they move in different directions; they are generally out of phase with each other; they cannot reinforce each other; and their energy is diffused.

Coherent light is highly organized. Light waves are of the same wavelength; they move in one direction only; they are in phase with each other; they reinforce each other; and their energy is highly concentrated in an intense beam of monochromatic light.

The maser (*m*icrowave *a*mplification by *s*timulated *e*mission of *r*a-

diation) was the forerunner of the laser (*l*ight *a*mplification by *s*timulated *e*mission of *r*adiation). The laser is a device that produces coherent light.

In optical telephone systems, light travels by total internal reflection along optical fibers made of very pure glass of hair-fine thinness. It was necessary to make tiny efficient lasers that could work with the fine optic fibers in the telephone system.

The development of the laser is based, among other things, on the discovery of the photoelectric effect and the formulation of the Quantum Theory of Light.

A quantum is a packet of energy. A photon is a packet of light energy. A photon is emitted when an "excited" atom drops back to its normal state. Pumping raises atoms to a high energy level. When there is a large number of excited atoms, population inversion has occurred. As they drop back to normal (ground) state, photons are emitted. When this takes place in a crystal, parallel to the axis of the crystal, other photons are given off, until finally a stream of them comes out of the laser as a coherent beam of light. Thus, light has been made more intense.

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